ELECTRICITY SUPPLY TRANSFORMER SYSTEMS AND THEIR OPERATION.

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BY

WILLIAM T. TAYLOR,
M.Inst.C.E., M.I.E.E., Fellow Amer.I.E.E., &c

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PREFACE.

THIS book deals with the power and lighting transformer from the practical operating standpoint. Those engineers engaged in the operation of transformers, which form a most important part of the majority of electricity supply undertakings now in existence, should find it useful. The book does not pretend to make an academic study of the fundamental basis of transformer design, which invariably involves assumed variables, nor does it deal with practical factory design, apart from a brief introductory guide; academic study largely ends at college and practical design at the factory. Almost the whole text deals with the more important practical questions which arise after the transformer has left the factory.

The book demonstrates that the various past and present standard practices now tend to cause engineers to be at variance in their opinions on many important questions, such as earthing *versus* insulating the neutral point, polyphase *versus* single-phase units, *delta* against *star* connection, core type *versus* shell type of units, multiple earthing *versus* earthing at the supply end only, making the most effective and most beneficial use of line capacitance *versus* making the most efficient use of inductance in the earthed neutral, use of 230 volts to neutral *versus* use of 115 volts to neutral for dwellings and works, use and safety of two transformers in series to make the *star* connection *versus* the same for the *delta* or the "*A*" connection, etc.; also on such questions as grading of the insulation strength on windings, methods of protection to be used, and size, type and class of unit to install for best future conditions, etc. These are some of the many questions discussed herein.

The International or World system, centred upon in the text, is the *three-phase system*. With the exception of Chapter IX, which deals with phase transformation involving the two-phase system, the whole text embodies universal use of the three-phase and single-phase systems—the former allows of no less than six different connections, namely: the "*A*," *delta*, "*T*," "*V*," "*Y*" and "*Z*."

It is with one or other of these six connections that initial choice and final deciding factors are concerned.

Of no small importance is the question of earthing; Chapter VIII shows why, how, where and when earthing should be made.

Differing from almost all other classes of equally or less important apparatus or machinery which forms a main link in a chain of operations and/or a system, the constant voltage transformer is flexible, adaptable, convertible, portable, and capable of being operated under a distinct plurality of conditions simultaneously. These various and complex methods of operation and systems of connections are also discussed herein. Also a new and quite original three-phase system is incorporated, the author having first put it into practical use, and now recently made it public.

The present work was written, and is especially intended for, engineers and operators of electricity supply undertakings in this and every other part of the world. The text has purposely been arranged to suit universal systems and practices calling for the highest and the lowest voltages, and for the largest and smallest capacities. It is made clear that, as the line is the cause of much more trouble and kVA carrying-capacity limitations than the transformer, it should be carefully designed and constructed in such a way as to meet the requirements of safety and maximum present and future kVA carrying-capacity, etc.

WILLIAM T. TAYLOR.

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CHAPTER I.

TREND OF TRANSFORMER PRACTICE.

THE general trend of opinion and practice has never been favourable to extra-high-tension generation, although such installations have been in operation for over forty years. We may or may not practise 33,000-volt generation, but should we do so it is recognised that at the generating end there would be a direct financial saving in transformers and their equipment and lower losses. However, these initial advantages do not solve the main problems of e.h.t. electric power transmission systems; in most cases a limit is placed on future extensions, due to the present limits in generator voltage.

The *transformer* is without doubt the most important piece of apparatus in the whole electricity supply industry. Without it, the National Electricity Scheme, and practically every electric power transmission scheme now operating throughout the whole world, would be commercially impossible. The transformer is required either in every a.c. station or on every a.c. distribution system throughout the whole world, and the scope of usefulness of the various types of transformers envelops the entire field of electrical engineering.

The purpose of the "constant voltage" transformer to be used on heat, light, and power supply (which type forms the subject of this text) is to step-up the generator voltage in the generating station in order to enable very much greater quantities of energy to be transmitted over far greater distances with very appreciably reduced losses compared with direct transmission from the generator, and to step-down the voltage at any desired point, such as at distribution stations, for direct or indirect supply to consumers; also, where power stations are required to be inter-connected with each other, independent of their respective voltages, to facilitate simple connection and ready transfer of loads, as also the transformation of energy or/and phases alternatively from one system to the other.

The transformer has no moving parts and it consists in its simplest form of a laminated iron core with two insulated coils on this core, the whole being immersed in a tank of oil. If these two coils have different numbers of turns, by applying a given voltage to one coil (called the *primary*), a voltage of another value will be obtained from the other coil (called the *secondary*). This is the case irrespective of whether the former is a high-tension or a low-tension coil; if voltage is applied to the low-tension coil we have a *step-up* transformer, and if voltage is applied to the high-tension coil we have a *step-down* transformer. Practically all distribution transformers have two primary and two secondary coils (windings) arranged so that they may be connected in parallel or series. The high-tension windings are almost always placed in series, while the low-tension windings are either placed in parallel or in series, to suit local conditions and requirements.

The transformer manufacturer can best co-operate with the operating engineer or/and the user by proper design, by the best selection of high-grade materials, and by adequate inspection and tests to prove that the design, manufacturing processes, and assembly have been properly carried out. The best design is usually that based on a close study of the class of load the transformer is to serve.

Transformers and loads may roughly be divided into three main groups, namely:

(1) Large station transformers feeding directly into a large system having a diversified load.

(2) Intermediate and other sub-station transformers serving certain industries which have a high load factor, or/and serving a diversified load.

(3) Distribution and service transformers which are on the line continuously and are called upon to deliver full load only a small part of the time.

The installed kVA capacity of transformers amounts to many times that of other electrical plant and equipment. This is because the transformer is required at the generating station and at several other points of the system before a supply is given to the ultimate consumer. With the recently installed National Electricity Scheme (called the "grid" system), the ratio of *indirect* or multi-transformations will still further increase.

Main power transformer service and distribution service are only as reliable as the weakest part of the transmission line or/and distribution network, which may have many weak spots. The

intermediate transformations and the distribution and actual service transformations are subjected to the many hazards coming in from the lines. The enemies of the system are usually from without, and there is reason for satisfaction so far as the transformer is concerned because it is so robust and reliable in itself. On the other hand, its safety depends on the manner of its installation, as also does its protection from external dangers. The designer does his part and it is up to the operator to adhere stringently to modern practices in the endeavour to obviate troubles and provide the best and the safest service. Once the transformer is placed in service it is dependent upon the line for its maximum flexibility for that service and for its safety and best operation, no less than upon its own internal reliability and performance.

The majority of transformers are of the single-phase type and are therefore as flexible and adaptable as the different line phase-conductors to which they are connected on both sides. For the most important installations it is always desirable to have a spare transformer and a spare line conductor available, and, for maximum efficiency of plant and system, such spares should rarely be idle. The transformer and the line should work together and be so laid out as to help each other over certain operating difficulties, which usually are of a single-phase character and in consequence favour the single-phase transformer where connected with flexibility and adaptability, etc. The line is the most susceptible to troubles of different kinds, and it should be designed and constructed with a maximum of safety, flexibility, and adaptability, no less than the transformer itself. At the same time the spare or auxiliary or duplicate conductor (or circuit) should always be in effective use, this also applying to spare transformers in general. Long years of practical experience, close observation, and careful tabulation of operating statistics, prove that a duplicate circuit is rarely more helpful than a spare single-conductor in tiding over line troubles; likewise, in the case of the transformers, greatest flexibility, adaptability, and minimum spare kVA capacity favour the single-phase unit in times of trouble, and these are the operating requirements to be borne in mind in the design, construction, operation, and maintenance of the whole transformer system shown in fig. 1.

Although the transformer will stand considerable abuse and exposure, its limiting operating feature is the temperature which the insulation will stand safely; its most dangerous enemy is lightning. Such features as longest life, highest efficiency, and safe operation, all start with the design; the after-problems begin

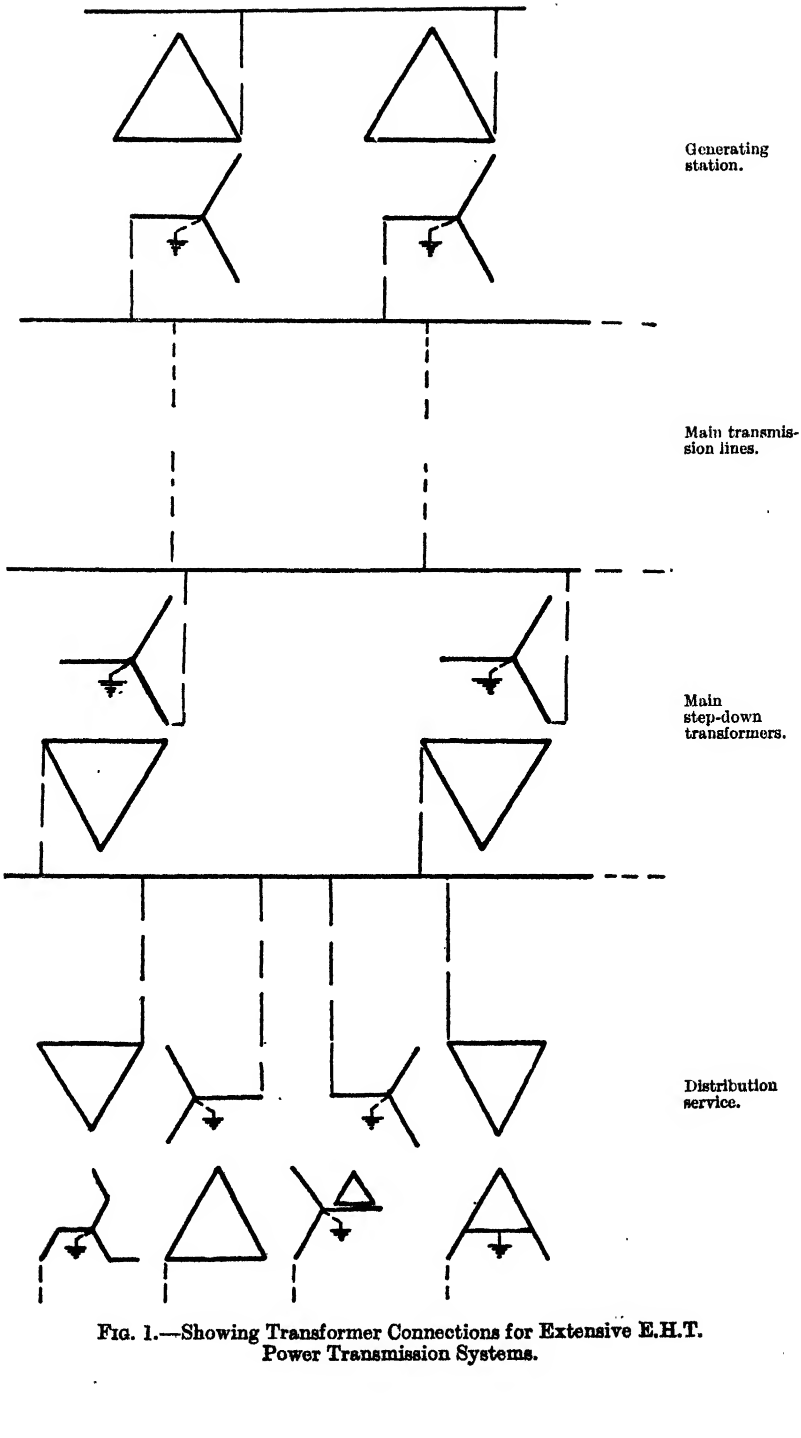


Fig. 1.—Showing Transformer Connections for Extensive E.H.T. Power Transmission Systems.

with the location, then come the installation, operation, and maintenance, all of which are more or less variable in character. A poorly designed transformer is handicapped from the start, so much so that its life may be very short, its efficiency low, its safety open to suspicion, and its operation and maintenance costly. All these are questions of great importance to the manufacturer, the purchaser, and the user, as they may bring unnecessary troubles and difficulties to the whole system. It is the operator's duty to make the best possible use of the transformer and apply its use to every condition whether it be simple or complex, and to normal or abnormal operating conditions. These are the problems discussed in this book, written throughout from the practical engineering point of view, especially for the operating engineer, student, and attendant. In actual practice, the operator little concerns himself with the theoretical or practical designing of transformers.

With regard to the size of transformers, there appears to be no limit; the difficulty is rather with the transportation of the unit. The largest polyphase self-cooled type of to-day is 3-phase, 50,000 kVA, with an overall efficiency of 99·54 per cent. at half load; there is also a self-cooled, 1-phase, three-unit bank of 130,000 kVA. Recently, a bank of three 1-phase units, designed for 16·67 cycles, were installed for electric traction supply, and it is estimated that when operating at the same frequency as the before-mentioned 130,000 kVA bank, they will have a total capacity of approximately 200,000 kVA.

CHAPTER II.

ASPECTS OF DESIGN FOR THE OPERATOR.

TRANSFORMERS are so designed that the transformation is undisturbed by unsymmetrical loading. They are designed so that the transformation will actually distribute the single-phase load as evenly as possible on the various lines of a polyphase system; also for stepping-up or stepping-down the voltage practically without any extra expense above the cost of the requisite transformers. Phase transformation is a different matter to voltage transformation; it is most satisfactorily accomplished when both the primary and secondary sides are polyphase, thus facilitating reversibility of the transformation.

The best type of transformer to use depends on the voltage, the permissible size, the location, and the requirements. On the basis of economy of material only, small high-tension units of the core type are favoured, and large low-tension units of the shell type; hence the reason why the latter type is so general for *service* and *distribution* transformers, and the former type so common in the various *station* installations. Small high-tension units have a relatively poor space factor, improving with increased size and decreasing voltage. It is recognised that, if the copper section has a low space factor, a reduction of the area of the copper section will mean a large reduction in weight of copper, and that, as copper cannot be used beyond a certain current density because of heating, and as iron cannot be operated beyond a definite magnetic density because of saturation of the magnetic circuit, we are, in practice, limited to a narrow range of magnetic densities in the iron, and about as narrow range of current densities in the copper.

In the core type of transformer we have a choice of several forms of magnetic circuit (rectangular, cruciform, etc.), also several forms of coils (disc, cylindrical, etc.); for the shell type there are about as many forms of iron and copper circuits to choose from. Only two kinds of transformers are in general use, namely, the single-phase and the three-phase. Both these are

designed to accommodate one or a combination of the various cooling systems, which are natural convection and radiation, oil-immersion self-cooling, air blast, oil-immersion water-cooled, forced-oil cooling, or a combination of circulating oil and water or/and jets of air.

In any transformer, only a part of the primary flux links the secondary, as part of it strays away from the regular course and completes its path without cutting the secondary coil at all. Due to this, there is an increase in the voltage regulation above that which results from the impedance drop in the coils themselves. To reduce the leakage to a minimum it is necessary to interweave the primary and secondary coils in such a manner as to compel the flux to stay in the iron path. At no load there is little tendency for the magnetism to stray, as the iron path has less reluctance than the air, but under load conditions the load current sets up a counter flux which tends to cause the lines of force to cross the air spaces.

For the usual pole and structure-type of distribution transformers, the shape of the coils is not so serious a matter as with the large or medium-sized power transformers. For these latter, the inherent mechanical forces can be tremendous, and the safety of the transformer during short-circuit condition depends largely on the shape of the coils. Circular concentric designs are inherently strong for the radial forces, which tend to crush the inner coil and expand the outer coil; axial force tends to compress the coils along their length. It is important to have the primary and secondary coils assembled perfectly symmetrically, and to have the tappings preferably taken from the middle, depending on the system connections; the advantages of tapping from the middle is in the avoidance of line surge dangers.

The steel used in transformers is high-grade special steel, known by a trade name. It is carefully annealed to keep the core loss as low as possible. The magnetic circuit of the transformer is built up of laminated punchings of rectangular shape, which are carefully assembled and the yoke irons placed in such a manner that the air gap is practically negligible. The iron is worked at fairly low magnetic densities so that, by its proper assembly, the reluctance of the magnetic path differs very slightly from a magnetic circuit without joints, which condition ensures a low core loss and a small exciting current.

Safety and continuity of service are the prime requisites of a transformer. Careful attention in the use, maintenance, and quality of the insulation, perhaps more than anything else, is

necessary, because insulation is *the* vital factor in the operation of any transformer. It must be strong and reliable, both electrically and mechanically, so as to stand up indefinitely against the complex conditions that it will meet in service. It must be more than strong enough to withstand abnormal voltages and vibrations and sudden jars caused by short-circuits, lightning, surges, etc. Although an ample factor of safety is always allowed, the ordinary continuous operating voltage is rarely more than 10 or 15 per cent. above rated voltage.

The insulation used consists of the highest grades of insulating fibrous material, which includes press-board, paper, mica, linen, and cotton.[1] The materials are carefully selected before placing in the transformer, so as to get the maximum insulation strength. The insulation placed between the high- and low-tension windings and the core is also made up of insulating fibrous materials. The high-voltage coil layers are separated from each other by one or more thicknesses of braiding and of special grade insulating paper which has a very long, tough fibre. The line-end turns of high-voltage transformers have additional insulation to counteract line surges. The coils are impregnated, the gum used being insoluble in oil and practically impervious to moisture. The air and moisture are previously removed from the coils, and the gum is drawn into all parts of the windings by capillary attraction; to ensure thorough coil penetration, a pressure of about 130 lb./sq. in. is applied to force the compound into the windings. The transformer is then given a baking, lasting several hours; this impregnation treatment ensures greatly improved insulation strength of the windings, uniformly increased heat conductivity, and greater mechanical strength of the windings, together with less chance for the windings to absorb moisture.

Of the two types of transformer (core and shell) in general use, the core type is the one having the widest field of usefulness, constituting more than 80 per cent. of the total. For small and large high-tension core transformers the coils are circular in shape. The windings differ, depending on the size and voltage of the unit; a common style is the open or drum, using square or flat (ribbon) copper strap for the low-voltage or the high-voltage windings, although the latter windings are sometimes made with round wire. The circular-coil construction ensures a uniform strain of the wire and offers the strongest possible construction. Several conductors are sometimes used in parallel to reduce or eliminate eddy-current losses, and the different layers of the wire are wound

[1] See the standard *B.E.S.A.* insulation pressure tests, in Specification No. 171.

straight across the entire coil. Usually, the high-voltage coils are wound with flat strap, one turn per layer, but in the relatively smaller high-voltage transformer the high voltage is divided between a number of coils, wound with a few turns of round wire per layer to keep down the voltage stress. High-voltage power transformer windings are impregnated with an oil-proof compound consisting of a high-grade insulating varnish, into which the coils are dipped several times and then baked. This varnish fills in the cotton covering, firmly binds the wire together, and forms a solid and well-insulated coil, well protected from moisture.

In the large high-tension station type of power transformers the copper width of the windings may become very great, since the radial thickness of the cylindrical winding must be kept as small as possible on account of the additional losses otherwise occurring. For the very large sizes, where the current is heavy and the copper cross-section large, difficulties are encountered in forming the windings, and in operation there is danger of insulation and coil deformation on short-circuit. To overcome this, flat conductors are used, arranged about each other radially, and connected in parallel so that each disc-coil forms a turn and the whole coil is in the form of a spiral. The coil is subdivided into as many equal groups as there are parallel conductors. When winding the coil the conductor lying on the inner circumference of one group is placed on the outer circumference of the next. In this way each of the parallel conductors passes through the different stray fields in the same manner. Besides the symmetrical distribution of current, this style of winding offers the advantage of providing oil ducts between turns and also ensures a higher factor of the insulation between turns. The great radial width of the winding as compared with the cylindrical type also ensures a free-pressure mounting with greater immunity from short-circuits.

Much progress has been made in the actual design and manufacture of transformer windings, so that it is now possible to produce very large and heavy windings of the disc-coil type without a single joint throughout their entire length. On many large e.h.t. power-transformer windings massive insulation reinforcement is provided as well as static shields. The latter supports the insulation strength and takes advantage of the fact that, at ordinary standard frequencies, the capacity and inductance of the transformer windings are in a stable condition, and that a sudden increase in the frequency, due to a surge or high-frequency disturbance, will produce an uneven voltage distribution through

the winding. As a general rule, heavy insulation reinforcement is placed on the end-turns of the windings to cope with this disturbance. The use of static end-shields is to ensure a uniform voltage distribution throughout the windings.

For small and medium transformer-outputs the losses and the magnetising current must be low; it is also desirable that transformers be rid of " hum." As the output increases there is also the problem of the heat produced in the iron core and the safety against fusion of the iron laminations in consequence of excessive heat. In transformers where this can occur, butt jointing of the laminations forming the cores and yokes should be avoided, and the laminations of any two parts should be made to envelop one another (this is a very old practice but is not always followed). By this means the no-load current can be made lower and the "hum" caused by the magnetisation can be reduced.

For service and distribution transformers the iron losses are particularly important, since they are continuous because the transformers are always in service. The iron loss could be reduced by increasing the copper loss of a given transformer if the change thus made would result in a net saving. As the iron loss is reduced the copper loss is increased, but this total loss occurs only when the transformer is loaded. There is, of course, the exciting current which is the cause of copper loss in the line and generator—a loss that is continuous so long as the transformer is in service; high exciting current also causes a lower power factor, thus affecting the regulation, and it is an indication that the iron in the transformer is worked very hard, near or past the knee of the saturation curve. A given transformer should be so related as regards these two losses that the cost of supplying them for a given service and period should be a minimum.

If a distribution transformer is to be used for a service on which the full-load demand exists for a short time only, the transformer should be designed for low iron losses; if this is carried too far, however, high resistance will develop and poorer regulation and unsatisfactory lighting service will result. After long service, if the trouble from high and non-uniform iron losses is not traceable to the quality of the iron, it may be caused by a circulating current in the windings, to laminations not properly insulated or enamelled, to magnetic cross-flux, or to a mixture of iron of different permeability. Eddy currents between laminations will also introduce an element of loss which increases as the square of the induction. With age and service the losses will increase, due to variations of one or more of the above-mentioned factors.

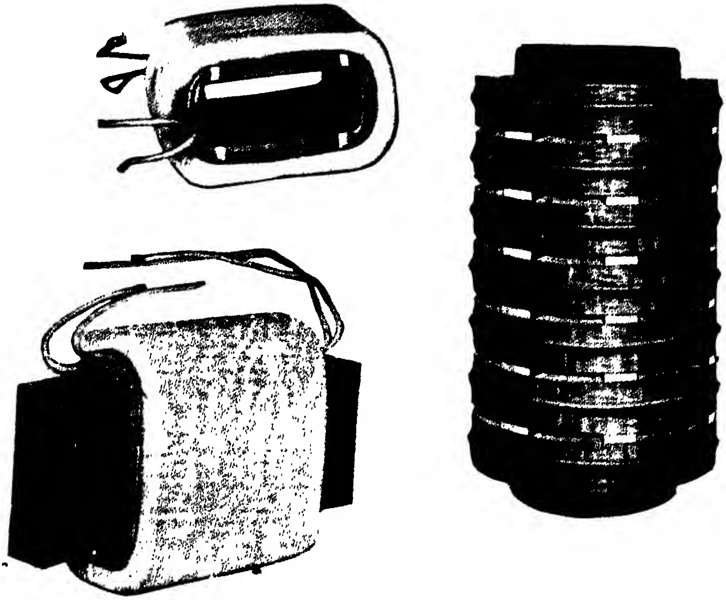


Fig. 2.—Showing Core Type of Transformer Windings.

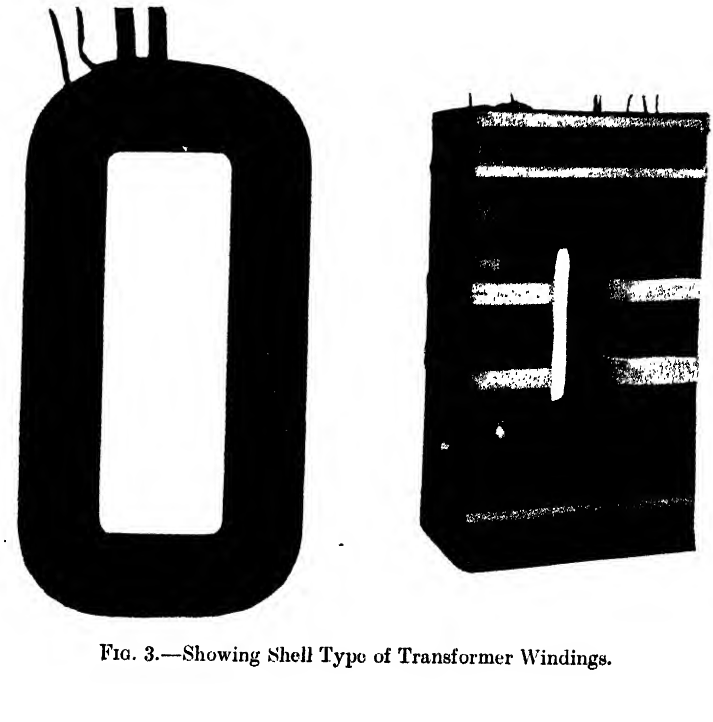


Fig. 3.—Showing Shell Type of Transformer Windings.

If the impressed voltage is decreased in a transformer, the induction in the magnetic circuit with the impressed voltage decreases the iron loss. The iron loss is proportional to a variable component of the magnetic induction, and the induction in the magnetic circuit is proportional to the impressed voltage on the winding. The iron loss varies approximately as the square of the voltage; thus, an increase of 5 per cent. in voltage will increase the iron loss 10 per cent. and *vice versa.* Moreover, the iron loss increases with a decrease in frequency; a 50-cycle transformer will have approximately 10 per cent. lower loss when operating at 60 cycles than at 50 cycles. It is possible to operate a 25-cycle transformer on a 50-cycle circuit and the iron loss will be decreased nearly 25 per cent.; it is impracticable to operate a 50-cycle transformer on a 25-cycle system because of the high iron loss, unless the voltage is lowered proportionally.

For small ranges of flux density the iron loss varies as the square of the flux density. At a given flux density the iron loss varies a little faster than the frequency. With a change of load on the transformer the iron loss will remain practically constant provided the voltage and frequency remain unchanged. For a given flux density the exciting current in ampères does not depend on the frequency. If the voltage is increased or the frequency decreased so as to magnetise the iron to above the knee of the magnetisation curve, the exciting current will increase. The exciting current increases with the flux density more rapidly than the iron loss, and for high-flux densities the increase is more rapid than for low-flux densities. By increasing the frequency on a transformer at normal voltage a decrease in flux density ensues, also a decrease in iron loss and exciting current together with an improved efficiency. The frequency may be decreased if the voltage is decreased in the same proportion; the flux density will be the same, but the iron loss and exciting current will be less. On the other hand, increasing the frequency will increase the reactance and the regulation will therefore be worse.

Eddy-current loss is proportional to the square of the thickness of the core laminations. The lower the eddy-current loss as compared with the hysteresis component, the thicker the plate or lamination which can be economically used. The thickness ordinarily used in transformers varies from about 0·0125 in. to 0·0179 in., and the induction density averages 35,000 lines per sq. in. for the usual transformers.

Copper loss is the energy consumed within the transformer to circulate current through the resistance of the windings; it is

divided into two parts, one is due to the load on the secondary side caused by the load current flowing in both the high-tension and the low-tension windings, and the other due to the exciting current occurring in the primary winding only, which latter is usually quite small for normal operating conditions. Copper loss appears as heat in the transformer. As a general rule, when the copper loss is low the iron loss is likely to increase rapidly.

In distribution transformers the copper loss is practically independent of the frequency. A copper loss from circulating currents in the windings will increase as the square of the induction, and may appear from paralleling different windings which have a slightly different ratio. The copper loss varies as the square of the voltage but decreases with an increase in voltage for constant kVA output. When the impressed voltage is low the current is large, and consequently the copper loss is increased; when the voltage is high, the current and copper losses are low. Since the copper loss of a transformer, including the eddy-current loss, is proportional to the square of the current in its windings, its value is given by E/I^2. To change the losses of a transformer for a given frequency and output, we may either impress a variable voltage on the primary winding or we may maintain a constant impressed voltage and vary the number of turns in the windings.

Study of the fundamental basis of transformer design is usually mingled with numerous assumptions because of the many variables involved, and the introductory guides mentioned here are intended to serve a useful purpose for the operator, for whom this book is written, when discussing the main fundamentals that enter into transformer design and influence operating conditions, and *vice versa*. The aspects of design given in this book do not take up the actual question of designing transformers, but rather the after-problems, beyond the manufacturer, showing how operation, in its various and complex forms, can best obtain the greatest usefulness and adaptability of the transformer in service. A knowledge of the fundamentals is an aid in making the best and widest use of transformers in service for normal and for abnormal operating conditions.

The fundamental equations of the transformer are characterised by the following relationships:

(*a*) The induction in the magnetic circuit is decreased, as is also the iron loss, as the number of turns is decreased.

(*b*) For constant impressed voltage, the iron loss will increase as the number of turns is decreased.

(*c*) As the resistance of the conductor (wire) increases with

length and smaller cross-section, the copper loss will increase with the number of turns in the winding.

(*d*) With a decrease in the number of turns, a shorter conductor (wire) length with greater cross-section will result.

If the dimensions of the iron core and the number of primary turns are known, the hysteresis and eddy-current losses can be separated by the following formulæ:

$$B = \frac{10^8 E}{4{\cdot}44 A f T}.$$

The iron loss may be found from

$$I_1 = \frac{V f k B^{1{\cdot}6}}{10^7},$$

and the magnetising component of the leakage current from

$$C = \frac{BL}{4{\cdot}44 T p}.$$

Since the resistance of a transformer is usually quite low, the ohmic drop is small and the voltage simply opposes the induced primary voltage so that, for a single-phase unit,

$$E = \frac{2\pi f TF}{10^8} = 4{\cdot}44 f TF 10^{-8},$$

and

$$kVA = \frac{4{\cdot}44 f TFI}{10^{11}}.$$

The voltage induced in the secondary is:

$$E' = 4{\cdot}44 f T'F \times 10^{-8}.$$

and the volts per turn are the same for primary and secondary, so that:

$$\frac{AfB}{3{\cdot}49 \times 10^6} = \text{volts per turn.}$$

The area of the core may be found from

$$A = \frac{F}{B}.$$

For distribution transformers the magnetic density ranges between 35,000 and 50,000 lines per sq. in.

In the foregoing :

f = frequency in cycles per second.
T = number of turns in series in the primary coil.
T′ = number of turns in series in the secondary coil.
F = total magnetic flux in the core.
V = volume of iron in the core.
B = number of lines per unit of area.
k = a constant, depending on the kind of iron used.
p = permeability of the iron.
L = leakage current $=\sqrt{m^2+n^2}$, where m is the magnetising component and n is the iron loss component.

The best design of transformer is that one based on the character of the load to be served. In designing a transformer for high efficiency, it is not difficult to carry the reduction of losses too far, and such reduction can be accomplished not only by using materials of low inherent loss but by reducing the amount of certain materials. By a reduction of materials, a transformer can be built that will pass all the required insulation and temperature tests, but such a transformer can well be a source of trouble and danger after a few years' operation. High quality should go with high efficiency, and high quality means greater safety, reliability, long and useful life, and a much cheaper transformer in the long run, in the same way as mentioned in Chapter X. respecting class of line.

The primary ampère-turns are always just equal to the secondary ampère-turns, but the advantages of transformer ratio become more pronounced in the different polyphase connections. The cross-section of the wire on high-tension windings is approximately 1/A times that of the low-tension windings, but a slightly greater weight of copper can be allowed on the high-tension side to compensate for the higher temperatures due to the use of thicker insulation. In ascertaining the number of turns required for the primary of a given transformer, knowing the number of turns on the secondary for a standard voltage, we need to consider the primary transformer connections (*star*, *delta*, etc.) and then apply the formula:

$$\frac{E_p T_s}{E_s},$$

where E_p is the primary voltage or ratio of transformation times the secondary voltage, and T_s is number of secondary turns. That is to say, for a *delta-delta* connected group of transformers let the number of turns on the secondary of each unit, *e.g.*, equal

120, the secondary voltage 400, and the ratio of transformation 15. The number of turns required for the primary winding will be

$$\frac{400\times 15\times 120}{400}=1800.$$

The voltage ratio is 6000/400.

A 25-cycle transformer, operated on 50 cycles and at low power factors, will give a very much poorer regulation when operated at 25 cycles. The regulation at 100 per cent. power factor is not affected appreciably by a change in frequency (f), since the ohmic drop is independent of the frequency. The reactance drop is affected by the frequency, however, and the regulation at low power factors will decrease with a decrease in frequency. The regulation will vary as the square of the voltage but will decrease with an increase in voltage for constant kVA output. The percentage regulation at $\cos\phi=1{\cdot}0$ is:

$$\frac{\text{Copper Loss}\times 100}{\text{Output}}+\frac{(\text{Percentage Reactance})^2}{200}.$$

Since the copper loss is not affected by frequency and the iron loss is increased by a decrease in frequency, a given transformer efficiency will be less at a low frequency than at a high frequency. The efficiency of distribution transformers in general will, at fractional loads, decrease with an increase in voltage, while the efficiencies at full loads or overloads will increase with an increase in voltage. In the proportioning of losses for distribution transformers, it may be better for good load-factor to sacrifice "all-day" iron losses in favour of lower copper loss. Conditions usually differ for any one extensive distribution system, so that it is impossible to design, for best efficiency, to suit all average requirements. The "all-day" efficiency is equal to the ratio:

$$\frac{\text{Output in kVA-hours}}{\text{Input in kVA-hours}}.$$

Thus, if a transformer is to operate most of the time on high or full load, it should be designed to have maximum efficiency at these loads; quite often maximum efficiency will be required at 75 per cent. of full load.

The total resistance of the primary winding, in ohms, is given by:

$$R=\frac{E\times\%R'}{100I},$$

and the percentage resistance drop in volts is:

$$R' = \frac{100P_c}{P}.$$

The total reactance of the primary winding, in ohms, is given by:

$$X = \frac{E \times \%X'}{100I},$$

and the percentage reactance drop in volts is:

$$X' = \sqrt{(\%Z')^2 - (\%R')^2}; \quad \text{or} \quad X'^2 = \%Z'^2 - \%R'^2.$$

The total impedance of the primary winding, in ohms, is:

$$Z = \frac{E \times \%Z'}{100I},$$

and the percentage impedance drop in volts is:

$$Z' = \frac{100Z_e}{E'}.$$

Where

E = primary rating in volts.
E' = h.t. rating of transformer in volts.
P = rating of transformer in watts.
P_c = copper loss in watts.
X' = reactance drop.
R' = resistance drop.
Z' = impedance drop.
Z_e = impedance volts.
I = full-load primary current.

The total copper loss in a three-phase unit is practically three times that in a single-phase unit. The copper loss relation is equally applicable to *star*- and *delta*-connected windings.

That is, copper loss per phase-winding for *star*-connection $= 0 \cdot 5RI^2$

and ,, ,, ,, *delta*-connection $= 1 \cdot 5R\left(\frac{I}{\sqrt{3}}\right)^2$,

where resistance per phase for *star*-connection $= 0 \cdot 5R$,

and ,, ,, *delta*-connection $= 1 \cdot 5R$.

The total copper loss for *star*-connection $= 1 \cdot 5I^2R$,

and ,, ,, *delta*-connection $= 1 \cdot 5I^2R$.

To find Z, the impedance drop, short-circuit the secondary terminals of the transformer through an ammeter and apply voltage to the primary terminals until approximately full-load current passes through the secondary ammeter; the voltage

necessary to do this is the impedance-voltage drop, ZI_s. The resistance drop, RI_s, of primary and secondary is found by passing d.c. through them and observing the voltage drop.

For protection against short-circuits, the reactance should be kept as high as possible in order to keep down the value of I_s. The value of the reactance will vary with the type, voltage, and output of the transformer, its location, and the system. For 50-cycle station-type transformers, the reactance varies between 4 per cent. for 500 kVA and about 10 per cent. for 10,000 kVA units. For a transformer having an inductance of, say, 0·002 henry, at 50 cycles the reactance is 0·628 ohm; for a full-load current of 200 ampères, the reactance-voltage drop is equal to 125·6 volts. Hence, for an 11,000-volt three-phase unit, the percentage reactance-voltage drop is:

$$\frac{125{\cdot}6 \times 100}{11{,}000 \times 1{\cdot}732} = 6{\cdot}6 \text{ per cent.}$$

The short-circuit current which can flow through the reactance with full voltage maintained at the primary side is equal to $\frac{100}{6{\cdot}6} = 15$ times the normal full-load current for the transformer, *i.e.*,

$$\frac{100 \times 200}{6{\cdot}6} = 3000 \text{ ampères,}$$

or,

$$\frac{11{,}000 \times 1{\cdot}732}{6{\cdot}6} = 3000 \text{ ampères.}$$

We therefore see that the impedance of a transformer enables the operator to calculate the current that will flow when the secondary is short-circuited for one reason or another. The percentage impedance of a single-phase transformer is based on its single-phase rating, and, when similar, the percentage impedance of a three-phase bank is based on the bank rating and is the same as the percentage impedance of the individual units making up the bank. Division of load can be found from formulæ given on page 95; also, the division of the current load between a plurality of units operating in parallel on single-phase circuits is given by:

$$I' = \frac{(P')}{(P') + (P'') + \ldots} \times I,$$

$$I'' = \frac{(P'')}{(P') + (P'') + \ldots} \times I.$$

Where

I' = load current of transformer bank (*a*).
I'' = load current of transformer bank (*b*).
I = line current for any given load.
P' = capacity rating of bank (*a*) divided by its percentage impedance $= \text{kVA}/\%I_iZ'$.
P'' = capacity rating of bank (*b*) divided by its percentage impedance $= \text{kVA}/\%I_iZ''$.

The normal impedance of distribution transformers ranges between 3 and 6 per cent. for the kVA capacity and voltages in general use.

The condition of high copper loss may be objectionable from the viewpoint of lowering the relative overload kVA capacity of the transformer. Such a transformer would most likely have a poorer regulation, especially at lower power factors, and would probably have the disadvantage of higher temperature in the windings. High "all-day" efficiency is important, but it should not be considered without a knowledge of relative initial or total cost, relative overload kVA capacity, relative impedance and regulation, relative insulation clearances and spacing for oil ducts, etc.

As an example of varying "all-day" efficiency (due to load conditions), for fixed efficiency of the transformer, we may take the following case: For a 20 kVA, 50-cycle, 6600 volts primary, and 230 volts secondary (400/230 volts with *star*-connection) transformer, supplying a lighting load for a residential district, it is estimated that the location of the transformer is such that it will operate at an average of two hours daily with full load, but only 1·5 hours at one-half full load, and, during the remaining part of the 24-hour day there will be no load. The transformer is designed for an iron loss of 330 watts and a copper loss of 440 watts, with an efficiency at full load of 96·3 per cent., an impedance of 3·2 per cent., and a regulation of 3 per cent. at 85 per cent. power factor. The problem presented is that of finding the "all-day" efficiency.

The "all-day" iron loss $= 330 \times 24$	$= 7920$	watt-hours.
The copper loss $= (2 \times 440) + (1{\cdot}5 \times 220)$	$= 1210$	,,
"All-day" total losses	$= 9130$	,,

The total daily energy output is:

$$(2 \times 20{,}000) + (1{\cdot}5 \times 20{,}000) = 70{,}000 \text{ watt-hours.}$$

The daily energy input is:

$$70{,}000+9130=79{,}130 \text{ watt-hours.}$$

Hence, the "all-day" efficiency is:

$$\frac{70{,}000}{79{,}130}=88 \text{ per cent.}$$

However, the true efficiency of the transformer is:

$$\frac{20\times 1000}{(20\times 1000)+330+440}=96{\cdot}3 \text{ per cent.}$$

Now, if we assume the same operating periods and the same efficiency of 96·3 per cent., but with 600 watts copper loss at full load and 170 watts iron loss, we obtain:

Iron loss $=24\times 170$	$=4080$ watt-hours.	
Copper loss $=(2\times 600)+(1{\cdot}5\times 300)$	$=1650$	,,
"All-day" total loss	$=5730$	,,

The daily energy output is the same as before, 70,000 watt-hours. But the daily energy input has been reduced, and is:

$$70{,}000+5739=75{,}730 \text{ watt-hours.}$$

Hence the "all-day" efficiency is:

$$\frac{70{,}000}{70{,}000+4080+1650}=92{\cdot}4 \text{ per cent.}$$

If, however, we invert these two losses so that the copper loss is 170 watts and the iron loss is 600 watts, we find that the "all-day" efficiency is no better than 82·5 per cent. The real efficiency of the transformer is the same as before, or:

$$\frac{20\times 1000}{(20\times 1000)+170+600}=96{\cdot}3 \text{ per cent.}$$

The efficiency of a transformer may or may not vary with different loads. With certain distribution transformers the copper loss is designed to be twice that of the iron, which condition gives a fairly constant efficiency over working loads. For instance, if a 20-kW transformer has an iron loss of 257 watts and a copper loss of 513 watts at full load, with 257 watts copper loss at half load, then the efficiency at full load is:

$$\frac{20\times 1000}{(20\times 1000)+257+513}=96{\cdot}3 \text{ per cent.,}$$

and the efficiency at half load is also

$$\frac{10 \times 1000}{(10 \times 1000) + 257 + 257} = 96 \cdot 3 \text{ per cent.}$$

The ratio of cost of iron to that of copper is often made equal to the ratio of copper loss to iron loss.

It is important for the operating engineer to devote his attention to improvement of the operating efficiency, which is not only dependent on the line copper and line construction, but also on the cost of energy at the transformer, which includes both line and transformer considerations (see Chapter X.). The "all-day" efficiency, as affected by variable conditions on the load side of the transformer, can often be improved in various ways. It is usually evident on most distribution systems that there is a considerable margin between the rated kVA capacity of station transformers and the total distributing-transformer capacity; the difference may well be 100 per cent. or greater. These conditions are due directly to the difficulties met in eliminating or controlling the variable load conditions at the point of delivering the service, and, because of these variable conditions, it is necessary to study such factors as the particular ratio of maximum demand to rated capacity, the ratio of maximum simultaneous load-demand to the sum of maximum individual demands, and the ratio of average input to maximum demand taken over short periods.

The copper loss increases with increasing temperature and the eddy-current copper loss decreases with increasing temperature. Like the line (see Chapter X.), the transformer should be judged by relative initial cost *plus* annual expenses, *i.e.* a higher first cost may be justified on the grounds that a greater expenditure at a later date will be avoided, just the same as in the case of the erection of a reinforced-concrete-pole line in place of a wood-pole line. The transformer is somewhat different from the line, however, in that it constitutes a larger unit for a fixed or given service or/and a unit specially designed for the particular character of load. Assuming a given efficiency, the question of cost is that of installing a transformer (or several units) adequate for the present load or for such a load as is likely to be required over the first three, five, or more years of its service; this initial sum should be added to or subtracted from the capital required to provide the extra transformer capacity, according to whether the smaller or larger transformer has the lower annual cost of total losses. It is evident that, if the annual cost of the losses can be reduced by the expenditure of an extra capital sum, such expenditure will

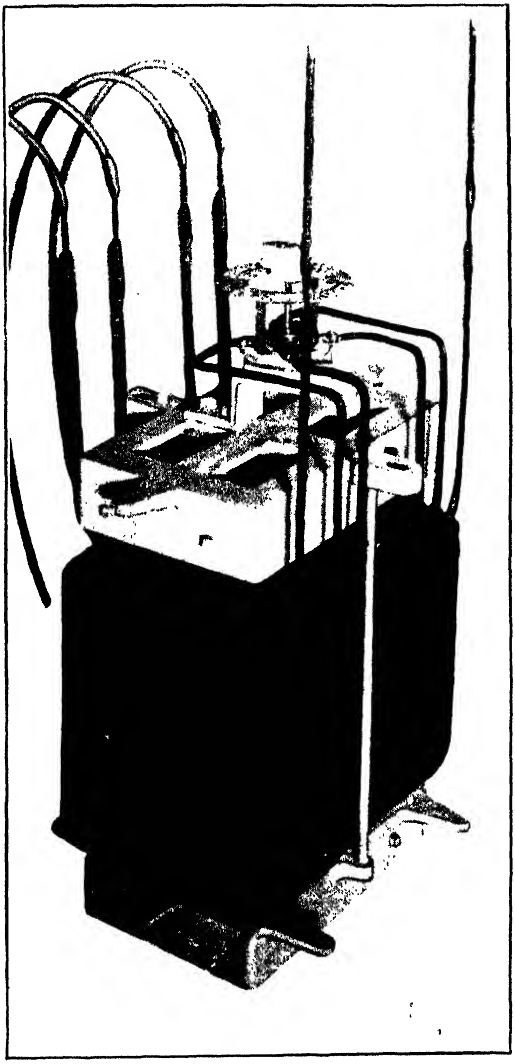


Fig. 4.—Showing Interior View of 10 kVA Distribution Type (*Exterior Tap-changing*) Transformer. (*Packard Electric Co., Ltd.*)

be justified if it does not exceed a certain amount, which figure is quite easily arrived at, just the same as is shown in Chapter X. for the line.

At a slight additional cost, transformers can be given from 25 to 50 per cent. overload capacity by increasing the copper and the cooling surface, so that if necessary they can carry 150 per cent. of full normal load without exceeding the normal 55° C. temperature rise. The efficiency of such a modified unit would be reduced somewhat during such an overload, but as this is an emergency condition the loss in kW-hours is practically negligible.

On distribution transformers several 2·5 per cent. voltage taps are usually provided to compensate for the variations in line voltage due to drop, and external tap-changing may be provided as shown in figs. 4 and 5. Also, regulators may be installed on the primary of lighting circuits; these are placed in series with the phase conductors at the station, and are set to compensate for the drop along the line to the feeding-point. Voltage regulation is also improved by not connecting load to the feeder between the station and the centre of distribution. Sufficient copper should always be provided to ensure good regulation to the distributing mains beyond the feeding-point. Sometimes compensators are installed in the neutrals of long radial circuits to compensate for the neutral drop in case of badly unbalanced loads.

For station and distribution types of transformers, voltage control is now effected by tap-changing on load; several satisfactory designs have been produced which enable tap-changing to be carried out directly on tappings from the main transformers. For the larger station sizes the tap section is bridged either with a continuously-rated or intermittently-rated reactor or an auto-transformer, with oil-immersed contactors for breaking the current. An excellent tap-changing method for service and pole-type transformers is shown in figs. 4 and 5.

A 5 per cent. reactor installed in series with a transformer terminal and outgoing feeder may result in a drop of only a fraction of 1 per cent. of line voltage (depending upon the power factor conditions) due to the side difference in phase-angle between the line voltage and the drop across the reactor. Thus, reactors of sufficient size to limit possible short-circuit currents to safe values can sometimes be used without seriously affecting line regulation. For protective purposes such an inductive coil is also of great practical value when placed in series with the transformer neutral and earth. The reactor, or inductive coil, is coming into more general use for various purposes where it is required to keep

down either over-current or capacity-current on o.h.t. systems. Of recent years the reactive coil has been used to bridge the tap sections for tap-changing under load conditions. On systems operating with isolated neutral, the inductive coil installed in series with the neutral and earth is now considered to be of much value in reducing the dangerous effects arising from arcing earths.

The cooling of a transformer is highly important. It is dependent on the amount of copper loss, the rate at which heat can be absorbed from the coils by some form of insulating or other medium, the rapidity with which the insulating medium circulates, and the area and condition of the tank surface. The requirements are low copper loss, large area of coil surface exposed to oil, rapid transfer of heat, use of oil of high viscosity, and large tank surface area.

As the load on a transformer increases, the temperature difference from copper to oil increases rapidly, so that for heavy overloads the temperature of the copper is much above that of the oil. It is therefore evident that, if it is necessary to put a heavy overload on a transformer for several hours, careful judgment must be exercised in trying to determine from the temperature of the oil what the temperature of the winding is.

In the oil-immersed type of transformer, during the time that the heat is being stored in the oil it is also being taken up by the circulating air if the transformer is self-cooling, which latter is the general rule. While the transformer is being heated up under a steady load, the rate of storing heat gradually decreases and the rate of giving up heat to the cooling medium gradually increases, until finally a steady condition is reached in which no heat is stored up but all is given to the cooling medium. The cooling medium (oil) has the capacity of storing considerable heat, so that if a transformer is operated at a moderate temperature, quite a heavy overload can be thrown on suddenly and carried until the oil reaches a temperature beyond which it is not safe to go because the temperature of the windings has approached the limit of safety. Due to the design and relatively greater exposure of the pole-type of service transformer, it can be suddenly overloaded with safety, especially the type shown in fig. 5.

The oil in transformers may be condemned not only on account of the presence of moisture, but on evidence of sludge, or thickening and darkening. When oil is condemned it may either be filtered or changed, depending upon conditions, an important condition being location and size and voltage of the installation. The B.E.S.A. has specified the intensified sludge test to be carried out

in the laboratory as that of passing air through the oil at a high temperature for two complete days with copper present in the oil. The slightest trace of moisture (0·001 per cent. water) greatly reduces the dielectric strength of the oil and consequently the insulation of the transformer itself.

Air, which is readily absorbed by the oil, gives rise to moisture and sludge due to the oxygen contained in it, and air bubbles impair the dielectric strength by distorting the electrical field and by engendering brush discharge on the e.h.t. windings. Sludge deposits itself on the transformer windings, gradually diminishing the cooling-duct spaces between the coils, decreasing the movement of the insulating medium and keeping it from the iron core and windings, forming creepage paths, and generally jeopardizing heat removal. Besides these disadvantages, such a state of the cooling medium leads to the formation of acids, which in turn endangers the quality of the oil, resulting in the destruction of the transformer if not discovered in time.

On station transformers it is the practice to use a conservator per unit or per bank of single-phase units; there is also the inert gas method, using nitrogen filling. To be effective a conservator must be so located that it provides an expansion chamber connected in such a way that there is no circulation of oil between the tank and the conservator while the oil volume remains constant. It must be placed in such a position that it is kept at as low a temperature as possible. The conservator allows only a small quantity of oil to be exposed to the atmosphere, and then only at atmospheric temperatures, and so avoids the conditions under which oxidation takes place.

An old but helpful practice in times of overload difficulties is to turn a motor-driven blower on to the tanks of transformers of the self-cooled types in particular. Depending on the type, size, and class of radiator used, from 25 to 50 per cent. increased output over and above the self-cooled rating can be obtained by the application of forced air draft or air jets, etc. Where oil sludge impedes the cooling, the application of air by jets or gusts, or any other cooling method, is of little avail.

Sludge in oil raises the viscosity, clogs the ventilating ducts, and results in a hot transformer. It can be prevented by a proper sealing against air inlet, by using the best quality of oil, by working at low operating temperatures and normal excitation; the main requirement is to keep the oil completely free from any contact with the air. Any transformer oil will, when heated in the presence of oxygen, decompose, and a precipitate will be formed,

consisting of *carbon*, etc. While this sludging has very little effect on the dielectric strength of the oil, the precipitate settles on the insulation and iron, where it forms a film of low-heat conductivity, so that the operating temperature increases, with consequent increase again in the sludging.

The breakdown value for transformer oil is around 22,000 volts with a 1-in. gap between disc terminals 1-in. diameter, or 40,000 volts with a 2-in. gap between 0·5-in. discs. Oil is considered in good condition when it will stand this latter test.[1] If the oil punctures at less than 33,000 volts with a 2-in gap, its dielectric strength should be brought to normal without delay. This can be done in various ways, the two most commou being by means of the centrifugal purifier or the filter-press, but the drier or reconditioning plant is coming into more general use, because it permits the oil to be dried, cleaned, and evacuated without having first to disconnect the transformers. The disadvantage of the various methods of cleaning and drying oil is the time taken up and the increased facility, during the process of cleaning, for air to come into contact with the oil.

The windings and cores of transformers should be examined annually for indications of sludge, and if present, the sludge should be removed by means of a jet of insulating oil under pressure, to prevent the occurrence of "hot spots" because of clogged oil ducts. After the sludge has been removed, the oil should be filtered and tested before it is returned to the tank. One of the best ways to remove sludge from water-cooling coils is to use gasoline or oil, together with scraping and brushing.

The extent to which the resistance of the insulation has been lowered due to the presence of moisture can be determined by various instruments, *e.g.* the *megger*; the insulation between the low-tension and high-tension windings and between each winding and the iron core, before the insulating materials have cooled sufficiently to absorb additional moisture, is measured. Comparing the values of the resistances found in this way with those for the transformer when dry and in normal condition will indicate the condition of the insulation.

It is very seldom that a leakage occurs from the water-cooling coils. When one is suspected, the coil should be thoroughly drained and a compressed-air pressure test made after the coil is filled with transformer oil. One end of the coil is capped, a pressure-gauge connected, and a pressure of about double the maximum operating pressure applied. This pressure is slowly

[1] Also see tests specified in *B.E.S.A.* Specification No. 171.

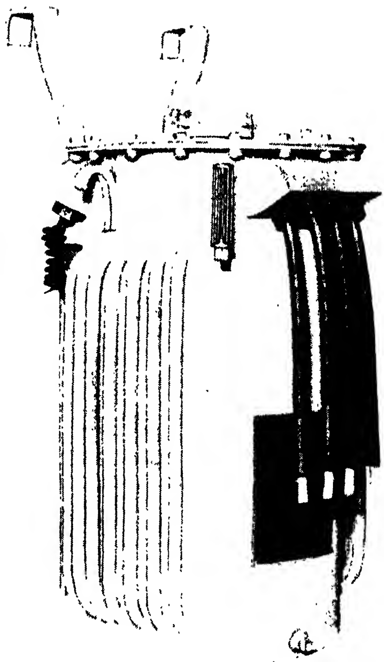


FIG. 5. Showing a Single-phase, Pole Type, 50 kVA, 3300/240-volt (*Exterior Tap-changing*) Transformer.

increased and kept at a value of not less than double the working pressure for several hours, assuming the coil does not leak. In this way, leaks can be discovered by a bubbling of the oil at the top, and as the insulating qualities of the oil in the tank are not further impaired, the test can be made without taking the transformer out of the tank. Only a very slight movement of the oil may be seen, but it can be made larger by lowering the oil-level so that the whole of the cooling coil is exposed. When draining the cooling coil from water it is necessary to apply compressed air to dry out before letting in the transformer oil.

The chief troubles with water-cooling coils are scale formation on the inner surface and sludge formation on the outer surface. Scale formation is indicated by measuring the flow through the coil by means of a flow meter, or by temporarily diverting the discharge into a measuring tank, at the same time noting the water temperature at the outlet and inlet; these should be checked with the measurements of flow and temperatures when the coils were originally installed. If there is any abnormal difference in the temperatures of the incoming and outgoing water when the flow is normal and the transformer is not overloaded, it is an indication that the cooling coils are clogged. Scale can be removed as mentioned on p. 154. When the scale has been removed, the coil should always be put under the pressure test already referred to before placing it into service. Cooling coils should be blown out by air under pressure about once a month to remove sediment. The pressure of the air for this purpose need not be greater than 100 lb.; each coil should be blown out several times.

CHAPTER III.

THREE-PHASE SYSTEMS.

THE advantages of the three-phase transformation, transmission, and distribution systems are acknowledged by the electrical profession universally.

For bulk power transmission the three-phase system has long since completely displaced the two-phase system. For distribution work, the latter system (including the five-wire, sometimes referred to as the *quarter-phase*, and on very rare occasions as the four-phase) has in actual practice almost become a remnant of the past, and, due to the recent unification of systems, etc. in this country, the two-phase systems cannot possibly retain their present status in the distribution branch of electricity supply, for which certain two-phase systems were at one time specially intended. The law has laid down unification of systems, etc. for the special good of the public, and a violation of this law is directly against public welfare. In view of this, it is considered unnecessary to make an apology for omitting a more general discussion of the two-phase system, apart from a reference in Chapter IX. The merits of the two-phase system are of such a nature as to take second place compared with the three-phase system when judged from practically all viewpoints, and more especially those concerning the general public, because the three-phase is to be the national system and already its costs and prices are such as to serve best the general public.

The two-phase systems, whether for three, four, or more wires, can be obtained from one or other of the three-phase transformations. In the case of the best of the two-phase methods, this can be done with the advantages of plurality of phase transformation to suit both systems, using *one unit* only, with almost all the required flexibility in the case of failure of one phase and with a perfectly symmetrical polyphase system (or for both systems working simultaneously) using a true neutral point for both said plurality of phases and systems, as shown in figs. 13 and 50. Also, by simple modifications, certain of the three-phase systems offer

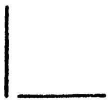
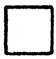
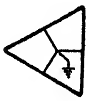
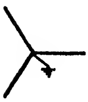
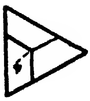
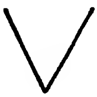
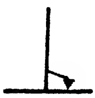
all the desired requirements for the optimum transmission and distribution system.

For a given distribution load there are more consumers per phase and less power per wire with the two-phase system, and consequently more hazards per phase, etc. Moreover, the two-phase system offers 33·3 per cent. greater hazards from induced excess voltages on the exposed ends of every group of transformers. As the larger number of phases for a given total number of conductors per system offers the greatest reliability (independent of greater flexibility, adaptability, general economy, and so forth) we see that the total numbers of conductors per phase for the two-phase four-wire and five-wire systems are in the ratio of 0·5 to 0·75 and 0·4 to 0·75 in favour of the three-phase three- and four-wire systems respectively. With one phase faulty or one conductor down, the two-phase systems will either collapse entirely and/or will be very dangerous (depending on the connections employed) if the windings of all transformers concerned are not arranged differently from the ordinary transformers required for the three-phase systems. As regards the advantage of possessing a true neutral point, the two-phase five-wire system is no better off in this respect than the numerous three-phase systems shown in fig. 6.

The choice of any particular system of distribution and transformation is determined by a close study of relative aggregate economy and simplicity, the nature of the load, the extent of the areas to be covered, the maximum possible advantages to all consumers, and many other considerations. It is not so much a matter of designing the most economical distribution system as of determining the best system to put in for present and *future* requirements, and more especially for the latter. In deciding on any method or/and system, it is advisable to look well ahead over a number of years and to plan the system and initially lay down the method or methods which will be fully capable of handling the load densities which are probable for a number of years to come, and also lay out the distribution in such a way that it will always be capable of expansion for the least capital outlay and least annual expenses, and with as few changes or modifications as possible, at the same time allowing the most economical and most reliable operation from the consumer's viewpoint (see also Chapter X.).

For most countries the urban areas will have underground distribution. However, whether underground or overhead, for a town of any size, the entire system will usually take its supply from the generating station or from a large substation, and such

FIG. 6.—Showing Relative Number of the Best and Most Symmetrical Two-phase and Three-phase Transformation Methods.

	Methods of Transformation for the Different Systems.	Number of Methods Available.
	*Two* single-phase transformers for 3- or 4-wire	2
	*Two* or *four* single-phase transformers for 4- or 5-wire	2
	*Four* single-phase transformers for 4-wire .	1
	Total . . .	5
	*One* three-phase or *three* single-phase transformers for 3-wire . . .	1
	*One* three-phase or *three* single-phase transformers and one *small* tertiary-*star* for 3- or 4-wire	3
	*One* three-phase or *three* single-phase transformers for 3- or 4-wire . .	2
	*One* three-phase or *three* single-phase transformers and one *small* tertiary for 3- or 4-wire	2
	*Two* single-phase transformers for 3-wire .	1
	*Two* or *three* single-phase transformers for 3- or 4-wire	2
	*Two* single-phase transformers for 3-wire .	1
	*One* three-phase or *two* single-phase transformers and one *smaller*, or a tertiary for 3- or 4-wire . . .	2
	Total . . .	14

(*Not* including, for the three-phase, the many combinations which can be derived from the *fourteen* different methods.)

systems taken as a whole will represent either *direct* or *indirect* transformation. That is to say:

(1) The system may take its supply from a main transmission line and feed into a large substation, and from the large substation step-down for supply to feeders, which in turn feed centres of distribution where the current is again stepped-down to supply the consumer's mains. This is called the *indirect* method of transformation. Or:

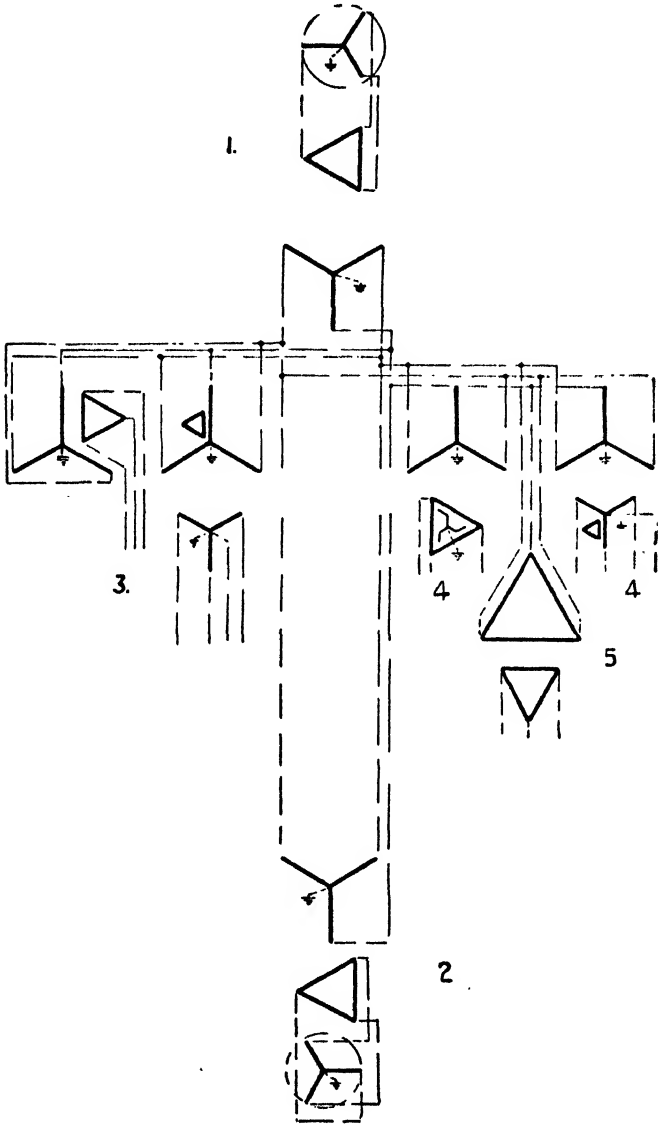
(2) The transmission line may feed into several substations and feeders extend from each of these substations to transforming centres (which may be vault-, structure-, or pole-type) to supply the secondary low-tension network or mains for consumer's services. This also is the *indirect* method of transformation. Or:

(3) The transmission may feed centres of distribution directly and/or pole-type transformers directly, and from these supply directly to the secondary low-tension network. This is called the *direct* method.

Depending on the magnitude of the transmission system and/or the voltage of the generator and the area to be covered, etc., there may be one or more transformations. The one-transformation, or *direct*, step-down method will prove the cheaper for the relatively smaller areas, etc. The multi-transformation, or *indirect* method, is more general and more flexible, and is the most economical where areas are very extensive and where the transforming centres must be located as close as possible to the centres of distribution. For this country, the multi-transformation (*indirect*) method will be the general practice. Apart from the various direct and indirect advantages of this method, it permits of the best selection of routes; it also has the advantage of relatively less length of high-tension circuit, or, alternatively, transformation to a higher voltage, less distribution points, and so forth. Multi-transformation usually makes live-line maintenance unnecessary for certain feeder schemes.

Where any one side (the primary or the secondary) is connected in *delta*, the flux variation is almost wholly suppressed by the circulation of triple-frequency current in the closed triangle. Therefore, from this point of view, the *delta* and the "*A*" connection on the primary or secondary side is desirable because it avoids the extra insulation stress due to the higher peak voltage, and prevents triple-frequency capacity current in the earthed conductor.

FIG. 7.—Showing Typical Present-day Three-phase System Connections. (Respective stations usually have several polyphase units or banks operating in parallel; these are omitted for simplicity.)



(1) Generating station, showing generators connected in *star* with earthed neutral; transformers for stepping-up are connected *delta-star*, *star* on the high-tension side with neutral earthed.
(2) Generating station located at large distributing centre. Connections the same as (1).
(3) Step-down station for large city and industrial centre; also for synchronous condenser.
(4) Step-down station for large distributing centre to supply power and lighting, etc.
(5) Step-down station for large industrial works.

Note.—Between the neutral point and the earth of each e.h.t. station of the system may be installed a relatively large power-capacity inductive winding (or "*reactor*") for the purpose of opposing the system charging-current due to earth faults by flash-overs, etc.

From the point of view of design and manufacture, there are only a few minor advantages inherent to either the *delta* or the *star* connection. These two connections are the principal transformer connections in use at the present time. The "*A*" connection referred to in the text is as yet unknown.

The *star-delta* or *delta-star* connected transformer (or bank) is far less sensitive to variation in impedances and ratios than the *delta-delta* connected three-phase transformer (or bank of three single-phase units); in fact, transformers having considerable differences in ratios and impedances can be used to make up a *star-delta* or *delta-star* bank without appreciably affecting the current or voltage division of the phases. Therefore, when a three-phase bank is to be made up of different makes of units or dissimilar units of (say) equal kVA capacity, more satisfactory operation can be obtained by connecting the units *delta-star* or *star-delta* or *star*-"*A*" than *delta-delta* (see page 94).

The relative kVA capacities, regulation, and suitability for large and small three-phase systems of the different transformer connections are shown in the following table:

TABLE I.

SYSTEM-CONNECTION RELATIONS.

	Connections of Systems.	No. of Single-phase Units.	kVA Capacity to kVA Delivered.	Regulation (Voltage).	Suitability for Earthed Secondary System.
1	*Delta-delta*	3	100 per cent.	Same as single-phase	Not suitable
2	*Delta-star*	3	100 ,,	,,	Suitable
3	"*A*"	3	100 ,,	,,	,,
4	*Star-star*	3	100 ,,	,,	,,
5	*Star-delta*	3	100 ,,	,,	Not suitable
6	*Open-delta*	2	115·5 ,,	Poor	,,
7	"*Z*"	3	115·5 ,,	Fair	Suitable
8	"*T*"	2	115·5 ,,	Poor	,,

The classes of satisfactory service that may be obtained from a three-phase four-wire *star-star* or *delta-star* or *delta*-"*A*" connected system, such as shown in fig. 8, and (*a*), (*e*) of fig. 9, also fig. 13, are:

(*a*) Single-phase two-wire, between the true neutral point and any one of the three phase-conductors, for lighting.

(*b*) Single-phase two-wire, between the tapping point and any phase-conductor, for light and/or power.

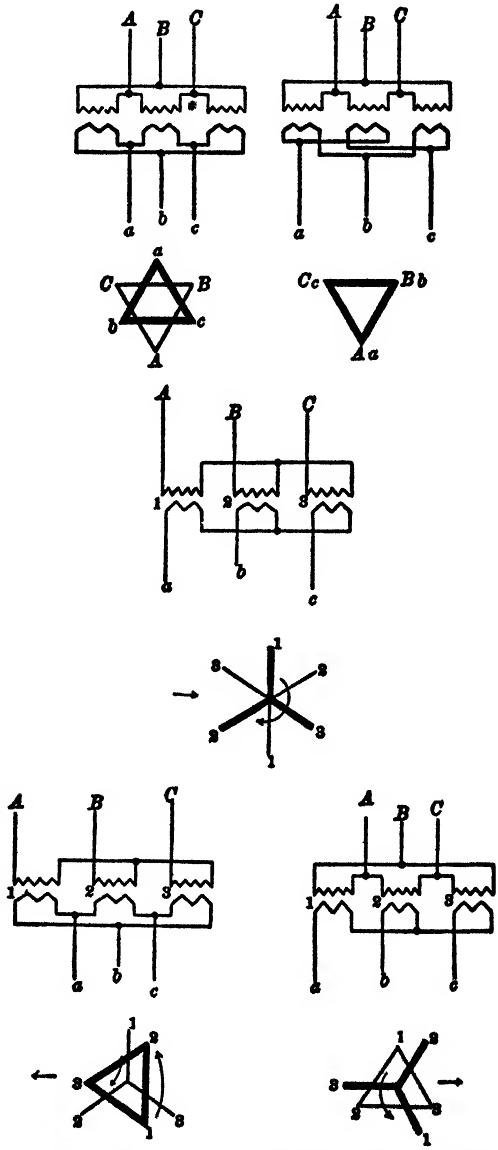


FIG. 8.—Showing Three-phase System Transformation.

(*c*) Single-phase three-wire between tap (or neutral) point and both ends of any phase-winding.

(*d*) Single-phase three-wire, between the neutral point and any two tappings of the three phases.

(*e*) Three-phase three-wire, between the three phase wires, for three-phase power.

(*f*) Three-phase four-wire, between the tap (preferably the neutral) point and the three phase-conductors, for *combined* light and power service.

Table II.

Relative Maximum Voltage Stress for the Most Useful Three-phase Systems, with Earthed Neutral.

(By the *Indirect* (Multi-transformation) Method.)

Transformer Connections.	Relative Maximum Voltage.				
	On Phase Unit.		Between Phases.		To Earth.
	Step-up.	Step-down.	h.t.	l.t.	
Delta-“ Y ” to “ Y ”-“ Y ”	1·000	1·000	1·000	1·000	0·577
Delta-“ Y ” to Delta-“ Y ”	1·000	1·000	1·000	1·000	0·577
† *Delta-“ Y ” to “ Y ”-delta*	1·000	1·000	1·000	1·000	0·577
† *“ Y ”-delta to “ Y ”-“ Y ”*	1·000	1·000	1·000	1·000	0·577
† *“ Y ”-“ V ” to “ Y ”-“ Y ”*	1·000	1·000	1·000	1·000	0·577
† *“ Y ”-delta to “ Y ”-delta*	1·000	1·000	1·000	1·000	0·577
Delta-delta to “ Y ”-delta	1·000	1·000	1·000	1·000	0·577
“ V ”-“ V ” to “ Y ”-“ V ”	1·000	1·000	1·000	1·000	0·577

(By the *Direct* (Single-transformation) Method.)

Transformer Connections.	On Phase Unit.	Between Phases.	To Earth.
† *“ Y ” to “ Y ”*	1·000 1·732	1·000 1·000	0·577 1·000
† *“ Y ” to Delta*	1·000	1·000	1·000
† *“ Y ” to “ V ”*	1·000	1·000	1·000
Delta to “ Y ”	1·000	1·000	1·000
“ V ” to “ Y ”	1·000	1·000	1·000
Delta to Delta	1·000	1·000	1·000
“ V ” to “ V ”	1·000	1·000	1·000
“ T ” to “ T ”	1·000	1·000	1·000

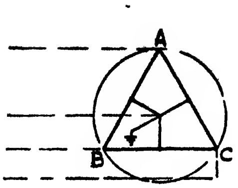
Note.—The last three systems do not have a “ neutral ” earth ; unearthed systems are subjected to a voltage to earth much higher than the normal value. † Neutral point of generator also earthed.

There are thus *six* kinds of service available from these differently connected systems, including the *delta-delta* system, and it would appear that the "*A*" system is especially favourable. The common three-phase four-wire *delta-delta* connection of the past and present is shown in (*c*) of fig. 9.

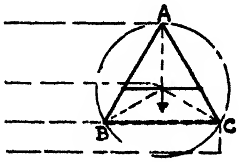
A disadvantage of the *delta-delta* connection is that no true neutral point is available and an earthed-neutral four-wire supply cannot be given; also, depending on the system voltage, there may be the disadvantage in that the windings for equal kVA rating are less robust than with *star*-connected transformers on the same system. Another disadvantage is that a short-circuit on one phase is practically a phase-to-phase short-circuit, and, when this occurs on the load side, heavier short-circuit stresses are put upon the windings. Furthermore, the insulation stresses are higher than with the *star* and "*A*" systems. In case of an earth on one line-conductor (assuming the common three-wire system of to-day, as shown in fig. 6) the voltage strain on the two sound phases is raised to 1·732 times normal; this excess potential, coupled with that due to the third harmonic component (assuming the system is converted to the open-*delta*) may weaken or break down the insulation or puncture weak spots on the line and in the transformers, but will not do so where transformers are connected as shown in fig. 13 (1).

On the other hand, the advantage of the "*A*" system is such that we can obtain a safe and satisfactory three-phase four-wire true neutral earthed system for combined light and power service. As a general rule distribution-type transformers, which constitute the great majority in use, can be built at less cost for the *delta* than for the *star* connection, and perhaps cheaper still for the "*A*" system. As the voltage decreases, so the advantages of the "*A*" system over the *delta* may increase. For the higher transmission voltages, *star*-connected transformers are found to be the cheapest; the cheapest system would be the *star*-"*A*", and not the *star-delta*, as hitherto understood.

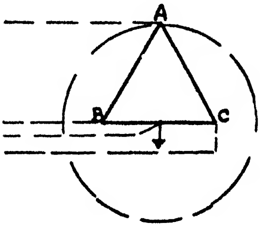
Another advantage of the "*A*" and *delta-delta* systems is that disabling of one unit, or phase unit, should not always put the three-phase unit, and rarely the three-unit bank, out of service, as the faulty unit can be cut out of circuit and the two remaining phases, or two single-phase units, operated either in open-*delta* or as "*A*," still retaining the three-phase three-wire for the former, and the three- and four-wire supply for the latter system. Perhaps the greatest disadvantage of the "*A*" system is the reduced output when a unit in the *delta* fails; nevertheless, the



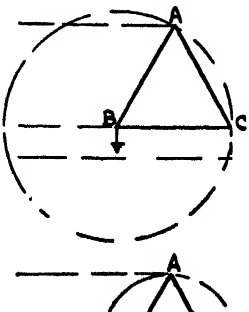
(*a*) Voltage to earth is practically balanced and is a minimum.
Load is balanced on all phases.
Facilities for balanced light and power loads, with minimum voltage to earth.



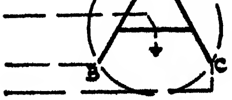
(*b*) Voltage to earth is practically balanced and is a minimum.
Load is balanced on all phases.
Combined light and power loads can be supplied with minimum voltage to earth for both services. (Using spare unit or winding between CB.)



(*c*) Unequal voltage to earth.
All lighting load is on one phase.
There are unbalanced voltages.
There will result unequal-sized conductors.



(*d*) Voltage to earth is unbalanced and is too high.
There are no facilities for combined light and power loads.



(*e*) Voltage to earth is practically balanced and is a minimum.
Load is balanced on all phases.
Combined light and power loads can be supplied with minimum voltage to earth for both services.

FIG. 9.—Showing good and bad arrangements for the operation of the three-phase three- and four-wire *delta-delta* and "*A*"-connected permanently earthed systems. The voltage to earth is seen to be a minimum for (*a*), (*b*), and (*e*), and a maximum for (*d*). For (*b*) connection, the transformer BC may (as desired) be considered as a spare and omitted as shown in (*e*), and, depending on the type of transformer used, and the arrangement of the windings, also respective loading of circuits, the impedances per phase may differ.

output is greater than the open-*delta* and there is less susceptibility to harmful circulating currents, etc.

From the following table it is seen that the "*A*" system is as reliable and as flexible as the best system, and it compares favourably with the *most* economical system. Each system has its particular merits, but the "*A*" system enjoys certain merits of both the *delta* and *star*, without the *star* tertiary. See also p. 45 for the merits of this system.

TABLE III.

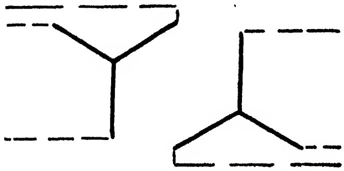
RELATIVE CONDITIONS OF SYSTEMS.

System.	Relative Total Windings Required.	Third Harmonic Current Flow to Line.	True Neutral Point.	Equivalent Symmetrical Light and Power Supply.	Most Desirable Use of Spare Unit.
Delta	173 per cent.	No	No	No	No
"*A*"	150 ,,	No	Yes	Yes	Yes
Zigzag	116 ,,	Yes	Yes	Yes	No
"*V*"	115 ,,	Yes	No	No	Yes
Star	100 ,,	Yes	Yes	Yes	No

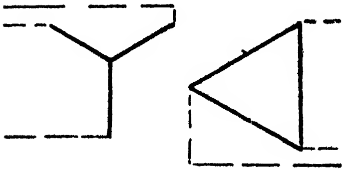
Delta-delta connected transformers must be wound for full voltage; on the other hand, the carrying capacity of each phase is only 57·7 per cent. of the line current. With the three-phase core type and *delta-delta* connection, a damaged phase cannot be completely isolated, due to the interlinked magnetic circuits, and operation of the open-*delta* or "*V*" connection is in consequence doubtful, depending on the particular type and arrangement of the magnetic circuits.

In general, the *delta-delta* connection is sensitive to variations in impedances and ratios. With slightly different ratios large circulating currents may result, depending on the difference in ratio and the impedances of the transformers or phases; moreover, when transformers have different impedances, the division of the load between them can be quite unequal. Although the *star-delta* or *delta-star* unit or bank, respectively, is less sensitive, it should not be overlooked that, if the kVA capacities of the units of a bank show much difference, the *delta-delta* and the *delta*-"*A*" connections will probably result in a greater combined capacity than the *star-delta* or *delta-star*, respectively, because, in the *delta-delta* or *delta*-"*A*" connected bank, the current will divide to a

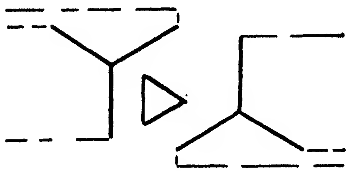
Fig. 10.—Showing Three-phase Transformer Connections (isolated neutral in each case) and the presence of Third-harmonic Current.



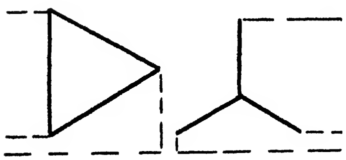
(*a*) With neutral on the primary side, this connection is very little used on account of its instability and unsatisfactory operating features. The core-type of three-phase unit does not completely suppress the third-frequency phenomenon.



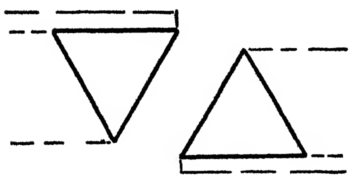
(*b*) With this connection the third-harmonic current will be exclusively confined to the secondary-*delta*, both when loaded and without load.



(*c*) With this connection of primary-*star* and secondary-*star*, and the introduction of a tertiary-*delta*, the system will operate satisfactorily without primary neutral.



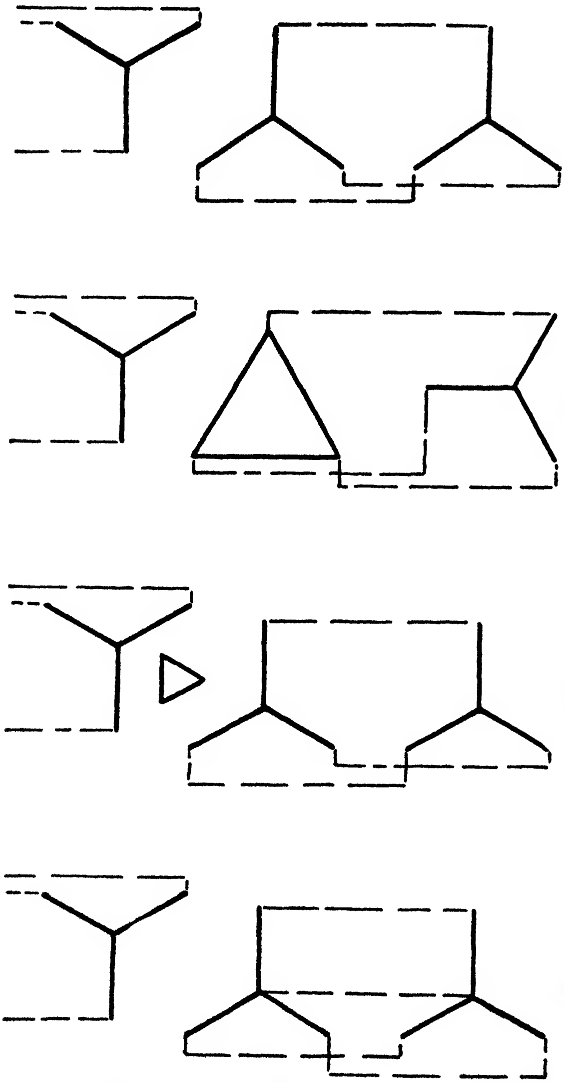
(*d*) With this connection the third-harmonic current cannot appear on the line but will be confined to the primary-*delta* for no-load and load conditions.



(*e*) With this connection the third-harmonic current will circulate in the two *deltæ* and therefore cannot appear on the line.

Note.—A weakness of the *star* connection *with neutral* is that the third-harmonic current can appear on the line.

FIG. 11.—Showing absence or presence and suppression of the Third-frequency Phenomenon in the various Three-phase System Transformer Connections, excluding generators, which are generally *star*-connected, and excluding the step-down secondary transformer connections which vary with local conditions and requirements.



(*a*) No third-harmonic current can flow on either side under any condition with this set of connections for primary and secondary.

(*b*) With this connection of system, the third-harmonic current will be confined exclusively to the *delta* secondary.

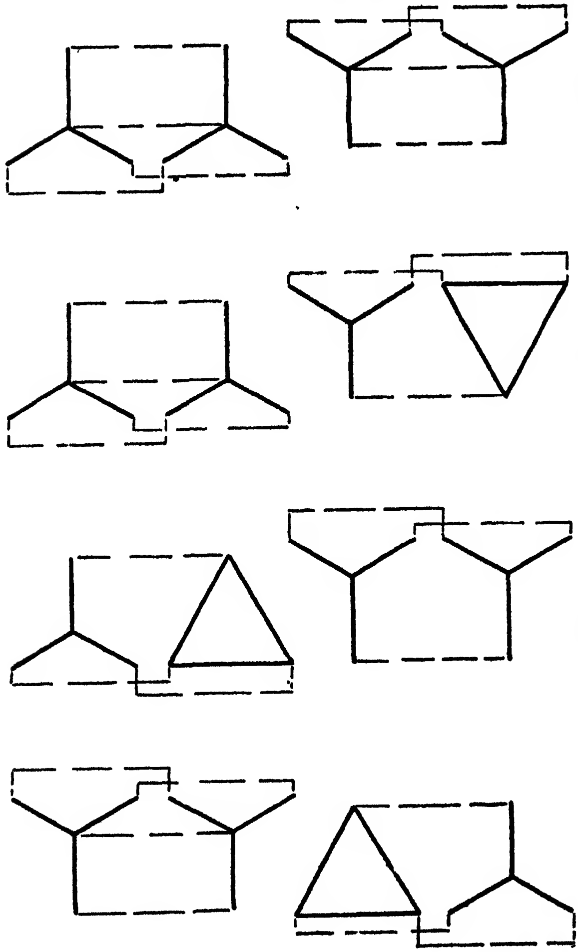
(*c*) With this set of connections, the third-harmonic current will be confined to the primary tertiary-*delta*.

(*d*) With this set of connections, the third-harmonic current will flow out on the secondary line when loaded.

Step-up transformers. Step-down, primary.

Note.—Generator connections are omitted. No commercial *star*-connected generator is entirely without a third-harmonic component in its voltage to neutral.

FIG. 12.—Showing presence, absence, and suppression of the Third-harmonic Current in the various Three-phase Transformer Connections from (and including) generator to the high-tension side of the step-down transformers. The "*A*" system is not shown because it is understood that it enjoys advantages of the *star* and *delta*.



(*a*) With this set of connections the third-harmonic current will flow in both sides when under load.

(*b*) With this set of connections the third-harmonic current will flow out on the primary side from the generator.

(*c*) With this set of connections the third-harmonic current will be confined to, and circulate in, the primary-*delta*.

(*d*) With this set of connections the third-harmonic current will flow in the primary line and circulate in the secondary-*delta*.

Generator. Step-up transformers. Step-down, showing primary only.

Note.—The third-harmonic voltage is practically eliminated when the primary neutral is connected to that of the generator, when a tertiary-*delta* winding is provided, and when the neutral of either primary or secondary is connected to the neutral of a *star-delta* transformer (or bank) across the line on the same primary or secondary side, respectively.

certain extent at least in proportion to the kVA capacity of the units, whereas in the *star-delta* or *delta-star* connected bank, respectively, the currents in all the phases are either exactly equal or about equal.

For the larger sizes and the higher voltage units, the cost of complete windings, and the cost of assembly, will be more for the *delta* connection than for the *star* connection, and, for the *delta* connection, more active material is required than for the *star* connection. A transformer for *delta-star* or *star-delta* or *star-"A"* or *delta-"A"* or *"A"-"A"* connection is less costly to manufacture than one for *delta-delta* connection; and, if full advantage is taken of the condition of relative insulation stress, the cost of the high-tension *star*-connection transformer will be lowered still further, but account should be taken of the higher peak voltage.

When a *delta* three-phase unit, or a bank of three single-phase units, becomes overloaded so as to necessitate an increased kVA capacity, the solution of the problem is usually that of installing a polyphase unit in the one case, or a bank of single-phase transformers in the other case, of greater kVA capacity. Obviously, such a change is very expensive, whether single-phase or three-phase units are employed, and for the single-phase unit installation it may be quite unnecessary. Industries in particular may not care to or may not be able to go to the expense of buying larger transformers just because the continuous load has increased, say, 15 or 20 per cent. beyond the full-load rating of the transformer installed.

To overcome this condition, two methods are available, namely:

(1) Change the *delta* connection to "*V*" or to "*A*" connection, and operate with two "*V*'s" in parallel, or with two "*A*'s" in parallel, using the spare transformer in either case. Or:

(2) Connect the spare single-phase transformer across any phase of the *delta*, in particular to the open phase-ends for the "*A*" connection.

The "*V*" and "*A*" connections, respectively, will permit of a greater total kVA loading of the transformers (*twice* 58 per cent. or 116 per cent. of the original total kVA for the "*V*") than the *delta* with a single-phase unit connected across any one phase; the voltage will be very slightly more unbalanced for the "*V*" connection. If several relatively small single-phase units are available (a spare unit can usually be obtained from some part of

the system, or from stock) they can be connected in multiple and then connected as one unit; this, of course, cannot be done with the three-phase unit.

The principal advantages of the open-*delta* (or "*V*") connection are: It is cheaper than a three single-phase unit set of the same capacity; it has about two-thirds of the core loss of a three-unit group; and it helps to tide over a complete shut-down. For distribution systems in general, these are most desirable advantages because of the vast number of transformer units involved in an extensive rural and urban distribution system, requiring low aggregate first cost and low aggregate "all-day" iron losses. The disadvantage of this connection is that two single-phase units (or the two phases of a three-phase unit) will furnish a load of only 58 instead of 66 per cent. of that of three single-phase units (or a complete three-phase unit) connected in closed *delta*, *i.e.* only 58 per cent. of the rated load of the original unit or bank, respectively. For a growing load, where the *consumer is charged for primary power* or load, and where the original investment is reduced to about two-thirds, and the consumer can increase the transformer capacity when the load reaches the amount determined by economy, there are advantages in using this connection, but the "*A*" connection may be superior. Where the load is low and the service subject to transient excess voltages and other external hazards, it may be advisable in some cases to disconnect the third unit of a bank of three single-phase units for continuing operation with greater safety and perhaps greater economy, and place it where it is safer, *i.e.* at a safe point of the two phase-units ("*A*" system), or disconnect it entirely. The former change may prove better.

Although only $\frac{100}{115}=86{\cdot}6$ per cent. kVA capacity for the "*V*" is available as compared with a closed-*delta* connection, when estimating a new installation for an industrial load, especially where several motors are installed, the total transformer rating may quite well be equal to the rating of the motors (the former in kVA and the latter in H.P.). For instance, take an industrial installation with a motor efficiency averaging 90 per cent. and a power factor of 85 per cent.; only two 20-kVA single-phase transformers are available for open-*delta* or "*T*" connection, whichever is desired. The equivalent in motor capacity would be

$$\frac{(2\times20)\times0{\cdot}90\times0{\cdot}85}{0{\cdot}746}=40 \text{ H.P.}$$

If no allowance is made for diversity and the fact that motors

rarely operate at full rated load for long, especially in aggregate, as in the case of several motors or a group of motors, then the total motor capacity is likely to be about

$$\frac{(2\times 20\times 0{\cdot}866)\times 0{\cdot}90\times 0{\cdot}85}{0{\cdot}746}=35 \text{ H.P.}$$

In many cases we should be justified in installing two 20-kVA single-phase transformers connected in "*V*" for a group motor-load of 40 H.P. or even higher. If three 20-kVA single-phase units had been installed originally, then, for open-*delta* ("*V*") connection, where a unit has burned out, the remaining two units would have a capacity of only 58 per cent. of the total, or

$$3\times 20\times 0{\cdot}58=35 \text{ kVA}, \quad \text{or} \quad [(3\times 20)-20]\div 1{\cdot}15=35 \text{ kVA}.$$

Of some practical interest are the various *closed-* and *open-delta* connections for parallel operation; several of the best combinations are given in the following table:

TABLE IV.

SHOWING EQUIVALENTS FOR THE BEST *Delta* AND "*V*" COMBINATIONS.

Connections of System.	Three-phase Capacity in Per Cent. of Single-phase Combined Rating.	Equivalent Number of Single-phase Units.	Number of Groups.
Delta	100	3·0	1
"*V*"	86·6	1·75	1
"*T*"	86·6	1·75	1
Delta-delta	100	6·0	2
"*V*"-"*V*"	86·6	3·5	2
"*T*"-"*T*"	86·6	3·5	2
Delta-"*V*"	80·0	4·0	2
Delta-delta-delta	100	9·0	3
Delta-"*V*"-"*V*"	72·0	5·0	3
Delta-delta-"*V*"-"*V*"	80·0	8·0	4

With either the *delta-delta* or the *star-star* connection the ratio of the voltages is the same as the ratio of the turns. However, with *star-delta* the ratio is

$$1{\cdot}732\frac{T_p}{T_s},$$

and with *delta-star* the ratio

$$\frac{E_p}{E_s}$$

is

$$\frac{1}{1{\cdot}732} \cdot \frac{T_p}{T_s} = 0{\cdot}577 \frac{T_p}{T_s}.$$

Thus, the same transformer will give *three* different ratios for the different connections, the highest ratio being

$$\frac{3}{1{\cdot}732} = 3 \times 0{\cdot}577 = 1{\cdot}732,$$

or *three* times greater than the lowest value. This is particularly important for the "*A*"-connected system.

Fig. 13 is shown for the purpose of presenting a clearer understanding of the relative merits of the combined *delta-star*, or "*A*" system, for the primary or secondary, or both, and for any voltage and any service. The service taken from it is *star* four-wire and/or three-, five-, or six-wire *delta*, and, if desired, instead of allowing spare transformers to stand idle, a unit may be connected across the open ends of the "*A*," which emergency practice permits a wide use of spare units as compared with other systems. The "*A*" system can be divided into three distinct phases of application, namely:

(*a*) A conversion of the open-*delta* or "*V*" system into the "*A*" system, shown in fig. 13 (1), to give both *delta* and *star* supply simultaneously.

(*b*) A conversion of either the closed *delta* [fig. 13 (2)] or/and the open-*delta*, or a change of the "*A*" system [fig. 13 (1)] into an increased voltage system without any change of the phase relations or of existing transformers, as shown in fig. 13 (3).

(*c*) A change or conversion of the "*A*" system half-windings, "*a*," to form a double open-*delta* or *star*, and connecting $\frac{1}{2}n$ winding (or n winding in multiple) to the respective *star* points, as shown in fig. 50. This change of connections applies either to fig. 13 (1) or to fig. 13 (3), or both, and gives a symmetrical and/or combined two-phase and quarter-phase system; also a direct phase transformation for three different two-phase relations, as shown in the top figure of fig. 50.

Comparing fig. 13 (2) with fig. 13 (1), the following are some of the outstanding points:

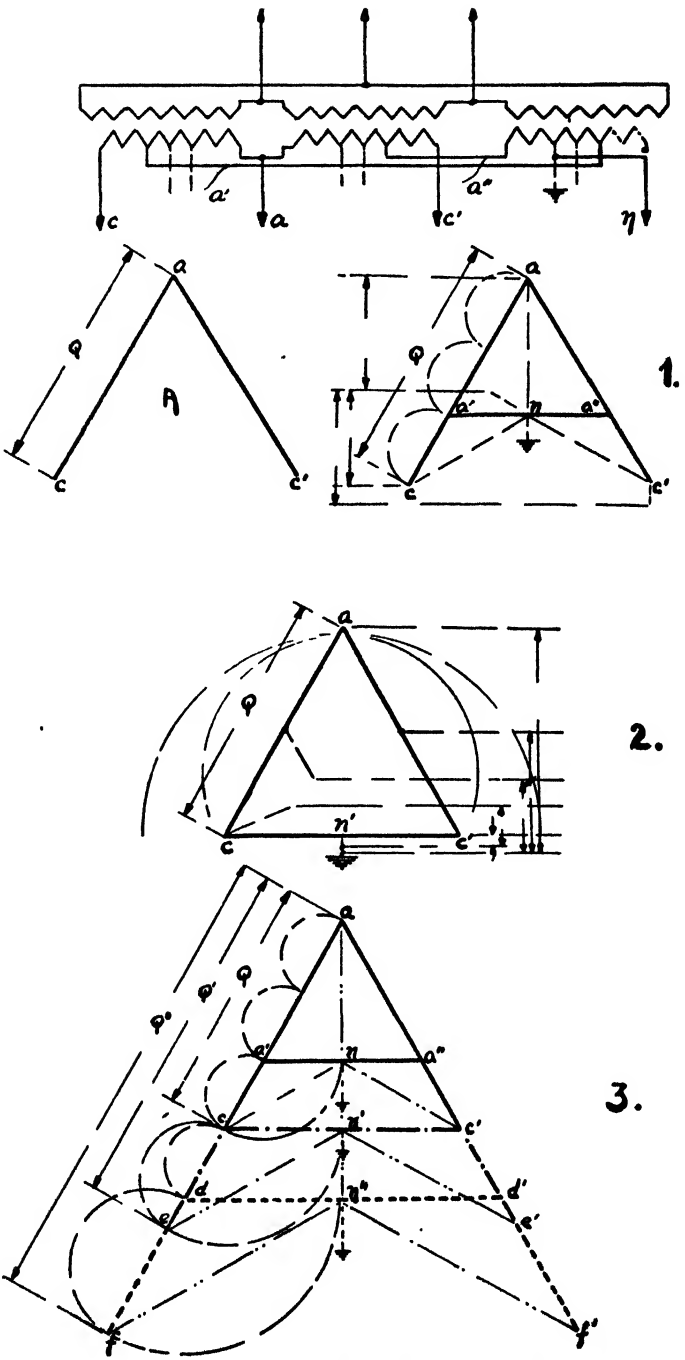


FIG. 13.—Showing the "*A*," or combined *Delta-Star* System. See also fig. 50, which is a direct conversion from the "*A*" system.

Fig. 13 (1).—This system requires less total windings than fig. 13 (2); it provides a true neutral point; third harmonic currents cannot flow out to the line as is the case with the open-*delta* system of fig. 13 (A); compared with the *star* and open-*delta* systems it prevents triple-frequency capacity current in the earthed conductor; it avoids the extra insulation stress due to the higher peak voltage; a symmetrical three-phase four-wire service can be given; a perfect system of earthing is established; it requires four wires as compared with six or seven wires for fig. 13 (2), and gives a better distributed lighting service; voltage to earth is brought to a minimum on all phases; it combines three distinct systems into one, namely, the *delta*, the *star*, and the "*A*" systems; it offers better protection and means for obtaining the same. Best impedance of phases will depend on design.

Fig. 13 (2).—This system is commonly used for the purpose of giving a lighting service from the *delta* while supplying power at a higher voltage. It is inferior to the "*A*" system for such a purpose; to supply a fairly symmetrical lighting load, six or seven wires are required, as shown in fig. 13 (2); the lighting voltage is lower than with the "*A*" system for equal phase voltage; a short-circuit to earth affects two phases, and with greater severity. Opening the *delta* for any reason allows third harmonics to flow out on to the line.

Fig. 13 (3).—Without disturbing the system shown in fig. 13 (2), or affecting the transformers, it can be converted to the "*A*" system; the same transformers can be used to increase the voltage in steps of 50 or 100 per cent. as shown in fig. 13 (3); the minimum amount of additional winding (one-third only) is required to convert the *delta* system to the "*A*" system and increase the voltage 50 or 100 per cent.; full use is made of existing transformers; there need be no change of line insulators for the 50 per cent. increase in voltage because the maximum voltage to earth is very little different from fig. 13 (2); the phase relations are not changed for *delta* or *star*, hence facilitating parallel operation of *delta-star* combinations, hitherto impossible.

Assuming equivalent kVA capacity phase-windings or single-phase units, the current-carrying capacity of the open-*delta* ("*V*") system is reduced to 58 per cent. of the closed *delta*. Closing the *delta* by the "*A*"-connection not only cancels out the 30 degrees phase displacement, but it results in a saving in kVA capacity to

an amount of nearly 15·5 per cent. *plus* a little further amount due to the changed phase relations, etc.; the larger part of this total kVA capacity thus gained may be deducted from that phase required for the smaller winding to form the "*A*" system.

Showing how the present *standard* voltages may be used with the "*A*" system of fig. 13 (3), take the following case for the secondary voltage:

Let *ac* and *ac′* equal 200 volts, then, *an*, *cn*, and *nc′* are equal to $200 \times 0{\cdot}577 = 115$ volts for lighting. On the other hand, if at any future date it is required to increase the voltage to the higher standard voltage, then, making use of the same transformers and same phase relationships, etc., we simply connect one phase-winding to the end of the other already in operation (without disturbing the service in any way) and make *af* and *af′* equal to 400 volts; then, *an″*, *fn″*, and *n″f′* are equal to $400 \times 0{\cdot}577 = 230$ volts for lighting.

The increase in primary voltage of 100 per cent. may be too high for total minimum cost, use of the same line insulators, and local requirements, etc.

The table on the opposite page shows that the "*A*" system facilitates the use of present standard voltages for transmission and distribution (primary and secondary).

It is estimated that, at the present time, in the U.S.A. and Canada, over 85 per cent. of Electric Supply Companies are using the closed-*delta* system for power supply, and over 70 per cent. are using the closed-*delta* four-wire system of fig. 13 (2) for combined light and power service. In view of the fact that the "*A*" system of fig. 13 (1) changes the voltage in steps of 50 or 100 per cent., and the fact that the general *standard* voltage practice is 460, 230, and 220 volts for power supply, and 115 and 110 volts for lighting service, it is evident that the "*A*" system is most suitable, flexible, and adaptable for change-over. The "*A*" system provides lighting from the *star* and power from the *delta* with a common neutral for both.

At the present time a vast number of distribution systems are at a stage where the primary and/or secondary voltage must be raised in order to avoid heavy power losses and poor regulation, and to allow for future expansion of the system. For those systems where the *delta*-connection and single-phase units are the general practice, cheapest, easiest, and best change-over can be made, and those *delta*-connected systems operating at primary voltages ranging from 2000 to 6000 volts, with secondary voltages between 110 and 230, possess the widest field of future usefulness.

TO BEST MEET PRESENT *STANDARDS*, WHEN CONVERTING FROM THE *DELTA* SYSTEM, THE ADVANTAGES OF SYSTEM VOLTAGES ARE SHOWN IN THE FOLLOWING:—

Delta SYSTEM.		*Star* SYSTEM.		"*A*" SYSTEM.		
Line to Line Voltage.	Maximum Voltage from Line to Earth. (See fig. 13 (2)).	Line to Line Voltage.*	Symmetrical Voltages from Line to Neutral.	Line to Line Voltage.	Same Voltage as the Original System.	Symmetrical Voltages from Line to Neutral.†
(1)	(2)	(3)	(4)	(5)	(6)	(7)
132,000	114,000	228,000	132,000	200,000	132,000	114,000
88,000	76,000	152,000	88,000	132,000	88,000	76,000
66,000	57,000	114,000	66,000	100,000	66,000	57,000
44,000	38,000	76,000	44,000	66,000	44,000	38,000
33,000	28,500	57,000	33,000	44,000	33,000	28,500
22,000	19,000	38,000	22,000	33,000	22,000	19,000
13,200	11,400	22,800	13,200	20,000	13,200	11,400
6,600	5,700	11,400	6,600	10,000	6,600	5,700
4,400	3,800	7,600	4,400	6,600	4,400	3,800
2,200	1,900	3,800	2,200	3,300	2,200	1,900
(*In the above,* (6) *and* (7) *refer to conversion from fig.* 13 (2) *to* 13 (3) *Q′*.)						
33,000	28,600	57,000	33,000	66,000	33,000	38,000
22,000	11,000	38,000	22,000	44,000	22,000	25,000
11,000	9,500	19,000	11,000	22,000	11,000	12,700
5,500	4,750	9,500	5,500	11,000	5,500	6,300
3,300	2,860	5,700	3,300	6,600	3,300	3,800
2,300	2,000	4,000	2,300	4,600	2,300	2,600
2,200	1,900	3,800	2,200	4,400	2,200	2,500
2,000	1,732	3,460	2,000	4,000	2,000	2,300
250	216	430	250	500	250	289
240	208	415	240	480	240	275
230	200	400	230	460	230	260
220	190	380	220	440	220	250
200	173	346	200	400	200	230
115	100	200	115	230	115	130
110	95	190	110	220	110	127
105	91	182	105	210	105	120
100	87	173	100	200	100	115
(*In the above,* (6) *and* (7) *refer to conversion from fig.* 13 (2) *to* 13 (3) *Q″*.)						
200	173	346	200	200	200	115
220	190	380	220	220	220	125
380	330	660	380	380	380	220
400	346	690	400	400	400	230
440	380	760	440	440	440	250
3,300	2,860	5,700	3,300	3,300	3,300	1,900
4,400	3,800	7,600	4,400	4,400	4,400	2,500
6,600	5,700	11,400	6,600	6,600	6,600	3,800
22,000	19,000	38,000	22,000	22,000	22,000	12,500
33,000	28,600	57,000	33,000	33,000	33,000	19,000
44,000	38,000	76,000	44,000	44,000	44,000	25,000
66,000	57,200	114,000	66,000	66,000	66,000	38,000
88,000	76,000	152,000	88,000	88,000	88,000	50,000
(*In the above,* (6) *and* (7) *refer to conversions from fig.* 13 (1) *A or* 13 (2) *to* 13 (1).)						

* Standard phase (or line) voltages are always required to meet standard transformer practice; very few of these voltages conform to standard practice. It will therefore be noted that the "*A*" system better meets all the requirements of line and neutral voltages for increase by 50 per cent. or 100 per cent. or for a decrease in voltage.

† It is only for primary and secondary *distribution* that these voltages are sometimes required to meet standard transformer practice—the more usual line to neutral voltages for distribution being 115, 230, 2300 and 3800, respectively.

On the other hand, the *star*-connected system has no reserve for future expansion; hence the reason why it is initially cheaper from the viewpoint of the transformer only, neglecting the fact that the lines connected thereto should always be considered an important part of the transformer system; the most restricted conditions apply to the *star*-connected three-phase unit system.

Almost without exception, the insulators and insulation on the primaries of, say, a 2000-volt *delta*-connected system will be quite reliable when operated at 4000 volts for either the "*A*" system or the *star*-connected system with earthed neutral—the maximum voltage to earth for both systems is fixed at 2300 volts, thus favouring the "*A*" system, because 2300 volts from line to neutral is originally required for the *star* system. We may therefore ask: "Why change to a restricted system such as the *star*?" Furthermore, "Why change the phase relations and why not have that system which is always ready for a partial or/and a complete system voltage change, and which makes the maximum use of existing transformers, *i.e.* the '*A*' system, which is better capable of meeting these changes, including parallel operation and interconnection, and at the same time provides a common neutral for the two distinct (but combined) system connections?"

If we change a 230-volt *delta*-secondary to a 400-volt *star*, or a 2300-volt *delta*-primary to a 4000-volt *star*, we do not obtain any increased kVA output from the existing transformers, except perhaps a slight increase due to the decreased I^2R loss caused by a changed current flow in the system for the same kVA delivered. An increase in line voltage from one standard value to another allows of an increased kVA carrying capacity of the transmission and/or distribution lines but *not* an increase in the kVA capacity of the transformers. Converting from *delta* to *star* means that we must provide a three-phase unit or three single-phase units for each existing unit on the system if further kVA output is desired, or if the *star*-connection is to be profitable or helpful. Converting a 200- or 2000-volt *delta* to the 400- or 4000-volt "*A*" system, with 230 or 2300 volts to neutral, offers advantages for either a gradual or sudden change-over, requiring only one additional (old) *delta* single-phase winding for the extension of one leg (one of the existing phases of the *delta* is used for the other leg) and two smaller windings, such as the two windings of an (old) *star*-connected bank, with the same neutral point used for the "*A*" system neutral, the two free ends then being connected to the respective one-third points of the two "*A*" legs. In most cases where the open-*delta* (or the "*T*" connection which, with inter-

changeable windings, provides the one-third points) is in common use, or where the primary *delta* connection is 2000 to 4600 volts and the secondary *delta* connection is 110 to 126 volts, and the respective voltages must be raised for any reason, the "*A*" system should prove specially useful, profitable, and flexible.

Assuming also that there is a two-phase four-wire system to be supplied from the same "*A*" system, then all that is necessary is to connect the two-phase system as shown in fig. 13A (*c*). If the two-phase service is 240 volts, then, for the afore-mentioned conversion from *delta* 200 volts to "*A*" 400 volts [see fig. 13A (*c*)], connect one lead of each phase at the same respective points of the "*A*" phase-legs as the two free ends of the neutral phase-winding previously referred to, and the other end of each phase (of the two-phase system) at the one-third point of the original *delta* winding of the opposite leg. For a higher two-phase voltage, connect the two leads of each phase to the respective bottom open ends of the "*A*" legs, and the other two leads of the respective two phases to the middle point of the respective *delta* windings; for 200 volts, connect at the points intersecting the neutral winding. Each phase-angle of the two-phase system takes up both sides of the "*A*" system, as shown in fig. 13A (c), left-hand figure. Thus, at least one set of tapping points is always available for the two-phase voltages.

The most dependable system with the maximum reserve of usefulness and flexibility is the *delta-delta*, and these advantages apply also to the single-phase unit. If, for any reason, it is required to convert the *delta-delta* system to *star-delta* or *delta-star*, the system still has a greater reserve of usefulness, etc., than the *star-star* system. Surely we want that system offering the greatest reserve of usefulness and flexibility and that system capable of future expansion? Surely we would not initially put down a system incapable of future extension? This latter is what we did when installing the lower-voltage system and when installing the *star-star* system. If an existing system is *delta-star* or *star-delta*, conditions are made worse by a conversion to the *star-star* system in order to obtain a higher voltage on the primary or on the secondary, as the case may be. The objections and difficulties to the *star-star* system can be mitigated to some extent by installing and connecting *delta*-tertiary windings in the *star*-connections; but why do this when it is better to convert to the "*A*" system?

The neutral point of a *star*-connected transformer is sometimes the reflection point in the case of certain travelling waves produced by induced voltages, which waves, at the place of origin, have the

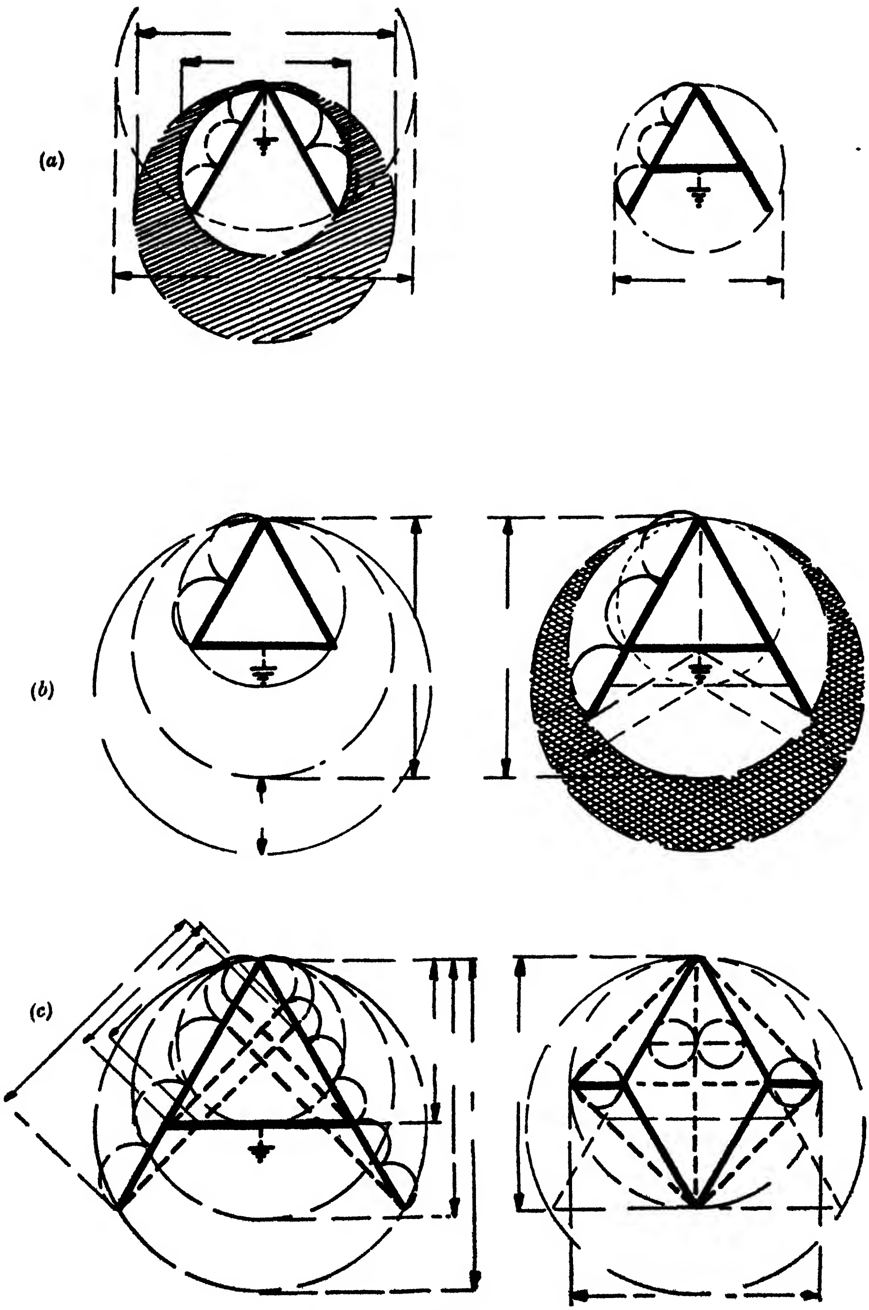


Fig. 13a.—Showing various Practical Uses of the "*A*" System.

(Where a spare single-phase unit is available it *may* (as desired) be connected across the two open base-legs to help pay for itself instead of standing idle in the station or stores.)

(*a*) Conversion from " *V* " (open-*delta*) to the " *A* " system.

The circles show the relative maximum voltage to earth for equal phase-to-phase voltage. The increase in voltage to earth of the open-*delta* (or closed-*delta*) compared with the " *A* " system is quite as high as the increase in voltage to earth of the " *A* " system with 100 per cent. phase voltage increase—this is shown in (*b*).

(*b*) Conversion from *delta* to the " *A* " system, showing a 50 per cent. increase in phase-to-phase voltage for the " *A* " system with equal voltage to earth for both systems.

The " *A* " system provides a *delta* and a *star* system with a common neutral point for both systems.[1]

The inner circle shows the full *delta* voltage as well as the " *A* " voltage above earth with a 50 per cent. increase in phase voltage for the latter system; the outer and middle circles show the *difference* in the " *A* " system voltage above earth for 100 per cent. increase in phase voltage, as compared with the *delta* of one-half the phase voltage. In other words, the potential stress for a 100 per cent. increase in phase voltage for the " *A* " system is no worse than for the *delta* or open-*delta* when compared with the " *A* " system of equal phase voltage.

(*c*) Conversion from *delta* to the " *A* " system, showing a 100 per cent. increase in the phase-to-phase voltage with 29 per cent. increase in the maximum voltage to earth as compared with the *delta* system of *one-half* the phase voltage.

In the left-hand figure is shown (with thick broken lines) *three* different ways for giving two-phase relations, and in the right-hand figure is shown two distinct two-phase relations—in all, there are shown four distinct two-phase systems and one quarter-phase system derived from the " *A* " system with the available tappings.

[1] See *Electrician*, 27th September 1929, for a detailed description of the " *A* " system compared with the *star* and the *delta* systems. For the " *A* " system, patents are pending in the name of the Author.

same amplitude and sign, and therefore travel with equal velocity if the line and transformer impedances are the same for each phase. *The travelling waves on each phase may either reflect at the terminals of the transformer or meet at the neutral point. No matter where the reflection point may be, travelling waves* do build up to several times their individual potentials and in this way produce excessively dangerous voltage stresses of a magnitude sufficient to destroy transformer windings, insulator bushings, etc. The most excessive voltage stress is always at the transformer terminals, not at the neutral point. The simplest and surest protective methods are to insulate the windings as mentioned on p. 70, earth the neutral point, and insert an arrester between the neutral and the earth.

Of recent years, transformers have been designed with three windings, the third winding commonly being called a tertiary winding. Such transformers must be relatively larger than the same units without the third winding. The tertiary winding should preferably be able to carry full-load current, although considerable flexibility is possible in this respect, favouring the "*A*" system. The load imposed on the three-winding transformer must be carefully watched, as it would be easy to overload any one winding. The total load must not exceed the rating of the transformer; this must hold regardless of how the capacities of the three windings are divided. Space limitation is also a problem in the design. Compared with the two-winding or ordinary transformer, the cost of the three-winding is somewhat higher, based on equal load-carrying capacity, because of the fact that certain parts of the circuit for the three-winding unit may be doing double the work compared with the same parts in the two-winding unit. There is also a difficulty in parallel operation of the three-winding transformer with the two-winding unit, and best results are obtained when the three-winding unit is operated in parallel with other three-winding units. In certain types of transformers the tertiary winding, inside and forming part of the transformer, can be used to advantage in case of trouble on one of the windings, but its best application as regards flexibility may seldom be suitable to maximum efficiency of the unit as a whole; the best all-round results are obtained when the tertiary is a separate unit. This type is mentioned here principally from the viewpoint of possible operating advantages.

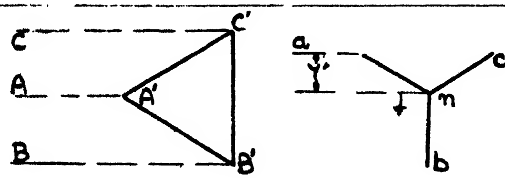
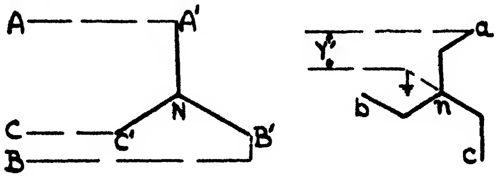
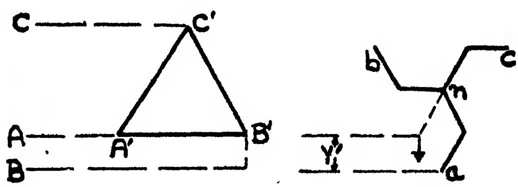
There are three different methods of obtaining three-phase supply from the more commonly recognised "emergency" single-phase transformer connections. These methods are:

(1) The open-*delta*, "*V*," three-wire connection (usually for power).

(2) The open-*star*, three- or/and four-wire connection with earthed neutral.

(3) The "*T*" (sometimes called "*tee*") three- or/and four-wire connection with earthed neutral.

FIG. 14.—Showing the common Three-phase Transformation Systems (*with* neutrals for the systems, respectively) available where loads can be *unequally* distributed on the different phases.

Primary.	Secondary.	(Primary.) (Secondary.)
A=0·577I B=0·577I A′B′=0·577I	*a*=I′ *n*=I′ *an*=I′ Y′=load	 (*a*)
A=0·577I C=0·577I A′N=0·577I C′N=0·577I	*a*=I′ *n*=I′ *an*=I′ Y′=load	 (*b*)
A=I/3 C=0·666I A′C′=I/3 C′B′=I/3	*a*=I′ *n*=I′ *an*=I′ Y′=load	 (*c*)

(The *star-star* connection cannot be used where a load is taken off one phase and the neutral, hence it is not included here.)

Methods (1) and (3) are usually considered on a par as regards windings and current overload, which are 15·5 per cent.; the former method is very commonly spoken of as an "emergency" connection, but the latter (which is little better) is seldom referred to as an

"emergency" connection, largely because it is so seldom used. Different winding arrangements and voltage ratios of units and taps are required for (3), and three units are often used, as compared with two single-phase units for (1) and (2). The slight *advantage of (3) over (1) is that only 86·6 per cent. voltage across one unit is required.*

The *delta-star* connection is widely used for stepping-up to supply high-tension transmission lines, as the third harmonic voltages are eliminated and there are inherent advantages of the *star* connection for high-tension, as will be recognised in what follows. The *delta-star* connection (with secondaries *star*-connected on the low-tension side) is also much used for stepping-down to supply three-phase four-wired earthed-neutral distribution networks.

The *delta*-star system has the advantage from an insulation standpoint whether the *star*-neutral is earthed or not. The mechanical stresses due to short-circuit may be the same for *delta-delta* or *delta-star*, but *delta* high-tension windings are not so well adapted to withstand mechanical shock as the stauncher windings for *star* connection; hence, assuming equal mechanical support, the *delta* high-tension winding will be mechanically weaker than the corresponding *star* winding. Several advantages of the *star*-connection on the high-tension side have already been mentioned, but these can be enlarged upon by giving the most important advantages of the *star*-connection which start for voltages at and about 11,000 volts: there are fewer turns per phase; the current per phase is higher, thus giving a higher copper space-factor and a cheaper transformer; the maximum voltage to earth is lower by about 42 per cent.; the average difference of potential between the windings and earth is only 29 per cent. as against 43·5 per cent. with the *delta* connection. Hence, the *star-delta* connection (*star* on the high-tension side) can be accepted as the most economical, firstly on account of the inherent combined advantages of *star*-connection for the high-tension, and secondly because of the inherent advantages of the *delta*-connection for the low-tension. The "*A*" system is a combination of the two systems *on both sides*, hence it enjoys the advantages of both.

Apart from the above-mentioned advantages, the *delta-star* and the *star-delta* connections, respectively, offer such advantages as: differences in impedance and ratios are to a large extent offset by a small magnetising current circulating in the *delta*, *i.e.* the *delta* (or "*A*") side circulates whatever third harmonic magnetising current there is and prevents its appearance on the line; the neutral

is made stable and can be earthed, so that the *star* and "*A*" systems give all the advantages inherent to an earthed system; a short-circuit in one phase of the *star* side does not affect the voltage on the *delta* side; a single-phase short-circuit on the secondary side will cause lower short-circuit stresses in a *delta-star* step-down unit (or bank) than in a *delta-delta* connection; and the *star* or the "*A*" connection provides a true secondary and/or primary neutral.

The different kinds of service that may be obtained from a three-phase four-wire *delta-star* or *delta-"A,"* or *star-"A,"* or "*A*"-"*A*" connected system (*star* or "*A*" on the low-tension secondary side), are:

(*a*) Single-phase two-wire, between any phase-conductor and neutral, for lighting.

(*b*) Single-phase two-wire, between any two phase-conductors, for power.

(*c*) Open-*star* three-wire, between any phase-conductor and neutral, for lighting.

(*d*) Open-*star* three-wire, between phase-conductors, for single-phase small motor service.

(*e*) Three-phase three-wire, between phase-conductors, for three-phase power.

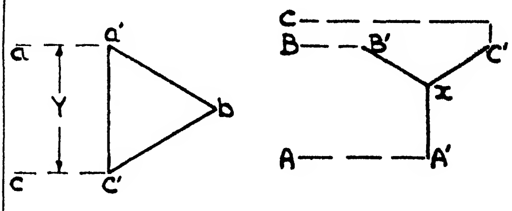
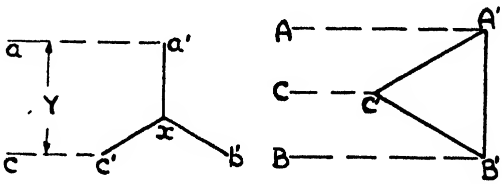
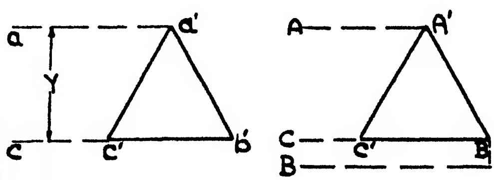
(*f*) Three-phase four-wire, between phase-conductors in the one case and between neutral and any phase-conductor in the other case, for *combined* light and power.

Furthermore, in three-phase transformation, the *delta-star* (or *star-"A"*) connection is the most economical way of obtaining good regulation between neutral conductor and phase-conductors in a three-phase four-wire system.

The disability of one phase of a *delta-star* isolated neutral system may render the whole bank (or complete three-phase unit) inoperative, except in a case where it is possible to change the voltage of the line connected to the *star* side of the transformers. This is particularly true where polyphase units or complete banks are operated in parallel and one-phase or single-phase unit fails. It is also possible if a line transmits power from one polyphase unit or complete bank of *delta-star* transformers at one end to other polyphase units or banks of *star delta* transformers at the other end; operation here perhaps can be continued in case of the disability of one phase (or one single-phase unit) by changing the *star*-connection to open-*delta* in both step-up and step-down transformers, thus reducing the line voltage to 1/1·732 of its

original value. Due to phase displacement all the transformer connections must be changed. The capacity of line and transformers will be reduced by a similar amount. By operating the system with an effective earthed-neutral we can obviate this

FIG. 15.—Showing the common Three-phase Transformation Systems (*without* the neutral connection for use on the system) available for unequally balanced loads on the phases.

Primary.	Secondary.	(Secondary.) (Primary.)	
$A=0{\cdot}577I$ $A'x=0{\cdot}577I$ $B'x=0{\cdot}577I$ $C'=0{\cdot}866I$ $C=0{\cdot}866I$	$a=I'$ $a'c=0{\cdot}666I'$ $b'c'=I'/3$ $a'b=I'/3$ $Y=$*load*		(*a*)
$A=0{\cdot}866I$ $A'C'=0{\cdot}577I$ $A'B'=0{\cdot}577I$ $B=0{\cdot}577I$ $C=0{\cdot}577I$	$a=I'$ $a'x=I'$ $c'=I'$ $Y=$*load*		(*b*)
$A=I$ $C=I$ $B'C'=I/3$ $A'B'=0{\cdot}577I$ $A'C'=0{\cdot}666I$	$a=I'$ $a'b=I'/3$ $b'c'=I'/3$ $a'c'=0{\cdot}666I'$ $Y=$*load*		(*c*)

(The *star-star* connection is not included because it is suited to balanced loads; it is inherently unstable unless solidly earthed, and unbalanced four-wire service is unsatisfactory.)

disadvantage and at the same time obtain other advantages over the *isolated*-neutral system.

It is commonly known that a *delta-delta* connected transformer system will continue to deliver three-phase power when either the high-tension or low-tension winding of a single-phase unit becomes damaged, but it is not so generally known that the *delta-star* or the

star-delta system of transformer connections will also continue to deliver three-phase power when the same *fault* occurs, and, more than that, it can do so when one phase-conductor is broken; see p. 164 and fig. 22. However, not unlike the afore-mentioned, when two or three complete banks are operated in parallel, the disability of one phase may render the whole of one bank inoperative; to give satisfactory polyphase service there may be disadvantages in disconnecting one unit from each of the sound banks metallically tied into the system. For satisfactory operation of this system with one winding of a single-phase unit damaged or/and the same phase-conductor on the *star* sides broken and disconnected, it is essential to have the neutral well earthed *at more than one point* and of low resistance. If the step-up transformers are earthed at the supply end *only*, satisfactory operation is usually doubtful. For a distribution network, with primary windings connected in *star* and the secondary windings in *delta*, if one single-phase unit should burn out, the neutral on the high-tension side can be made through a conductor such as the line phase-conductor of the damaged phase, failing which, through the overhead protection ground-wire or the overhead continuous earth wire, or, in case of dire necessity, the circuit can be completed by solidly earthing the *neutrals*, *i.e.* by multiple earthing.

For station-type transformers, which are usually of the larger sizes, *star-star* connected banks or units should have a *delta* on the metallic system, and it is customary to equip one bank or unit with the tertiary-*delta* winding. If, in the *star-star* three-core type, it is not necessary to carry a spare transformer, this type and connection will constitute the best choice *economically*, but not the most reliable choice. The three-phase three-legged core-type transformer may have some advantage in that it functions as if a high reactance tertiary were in circuit; this is due to the fact that triple-frequency fluxes must return through an air path, and because the shorted coil or winding serves as a short-circuit secondary to the other two coils or windings.

When transformers are connected *delta* or *star* on the primary to *star* on the secondary the impedance of the transformer (taken from the viewpoint of parallel operation) can be practically neglected in calculating the division of load between transformers in each complete bank. Transformers connected in *star* on the primary and *star* on the secondary divide the load in the same way. When secondaries are connected in *star*, the impedance and size of the transformers have no effect and the load divides practically

equally between the transformers and the banks. (See also p. 61 for advantages of this connection.)

In some cases it is desirable to operate in parallel with an existing *delta-delta* transformer another three-phase transformer, and to have the neutral of either the high-tension or low-tension available for earthing or relay operation or other purpose. This may be done as shown in figs. 9 and 13, or by making an interconnected *star* (*zigzag-delta*) winding as shown in fig. 16, both of which give the same angular displacement.

The *delta-star* connection is important because, for equal voltage between the primary and the secondary phases, respectively, it offers *three* times the ratio of transformation given by the *star-delta* connection. Taking an example: Let the voltage across the *delta* primary be 6600 volts and the voltage across the *star* secondary 66,000/1·732 =38,100 volts, making the ratio of transformation equal to 6600/38,100 =0·1732. The secondary line and winding currents are the same for the *star*-connection, and the ratio of transformation is 66,000/6600 =10. However, for the *star-delta* connection, the voltage across the *star* primary would be 6600/1·732 =3810 volts, and the voltage across the *delta* secondary would be 66,000 volts and equal to the line voltage, making the ratio of transformation equal to 3810/66,000 =0·0577. The secondary winding currents are 57·7 per cent. of the line currents, also 0·1732/0·0577 =3·0, *i.e.* three times the ratio of transformation for the *delta-star* connection. This clearly shows the advantage of the *delta-star* for step-up transformation and the *star-delta* or *star-"A"* for step-down transformation.

With the *delta*-connected secondary, if the primary is in *star* with the neutral conductor connected, an unbalance on the primary side will cause circulating currents to flow in the *delta*-connected secondary, but the *delta* or *"A"* connection on the secondary will tend to correct these unbalanced currents. If the neutral of a step-down bank is connected to the neutral of the system, the bank will tend to balance up any unbalanced load near that point on the system; in this case the step-down unit or bank of transformers must be large enough to carry its normal load and also the load that may be imposed upon it by any unbalance on the system near that point. For this reason there may be a disadvantage for a distribution system in connecting an artificial neutral of the unit or bank to the system neutral—depending on the kind of neutral provided (see figs. 9 and 18). In some cases we may connect the neutral of the bank of transformers to the system through a cut-out; then should a single-phase unit burn out, it

is only necessary to disconnect the unit from the bank and close the cut-out in the neutral conductor to operate the two remaining single-phase units in *open star-delta* or convert to the simple "*A*" system.

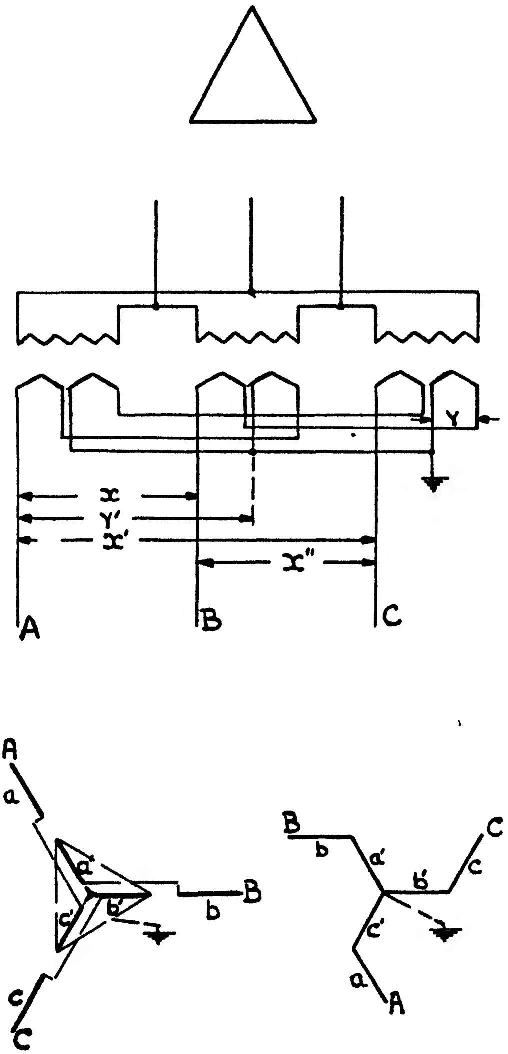
In its operating characteristics the *delta* side in a *star-delta* or *star-*"*A*" connected system (*star* on the high-tension side), performs two important functions, usually answering the two common questions as to why this connection is so extensively used for all voltages. It provides a local circuit for the triple-frequency components of the magnetising current, thus preventing triple-frequency pulsations of the phase-voltage, or triple-frequency *earth* currents (see fig. 10); and it serves to limit the magnitude of *fault* current in case of a short-circuit from line to earth, which is the more common fault. For the three-phase system, 3rd, 9th, 15th, etc. harmonics are simultaneously in the same direction in all three phases, or from line to neutral or *vice versa*; therefore, for a *star*-connected bank with unearthed neutral, these currents cannot flow. If the neutral of the *star*-connected bank and the supply end are earthed, these currents will flow through the earth. If the three-phase bank has a *delta* tertiary winding [see fig. 10 (*c*)] the triple-frequency currents will circulate in this winding, where they cause no trouble. With the "*A*" system this is unnecessary and all the advantages just mentioned are secured.

The "*A*" system converts the closed *delta* system into a distinct system either by extending two of the three phase-legs of the existing *delta* or by placing one of the three phase-windings the same percentage within the original *delta*, thus forming the letter "A" in each. As with the *star-star* system, there is no question of finding the neutral point; on the other hand, the *star-star* system has difficulty in providing means to keep the true neutral point from shifting.

In the *star-delta* connection the sum of the secondary induced e.m.f.'s must be zero on account of the *delta*-connected secondary; consequently the neutral point of the primary *star*-connection must be the centroid of the primary e.m.f. triangle. Since the neutral of the transformer unit or bank is stable it need not be connected to that of generator, and if it is desired to earth the primary *star* system, this can be done advantageously by earthing the neutral point of the unit or bank of transformers.

The *delta-star* connection and the ("*Y*"-"*Z*") *star-zigzag* [see fig. 17 (*b*)] connection have the same characteristics and will operate in parallel. Also, the *star-star* connection and the *delta-zigzag* (see fig. 16) connection will operate in parallel. All these systems should operate in parallel with the "*A*" system.

FIG. 16.—Showing Phase and Voltage Relationships for Secondary *Interconnected Star-connected* (more commonly called *Zigzag* or "*Z*") Transformer Unit or Bank of Three Single-phase Units.



Note.—Let $y' = E\sqrt{3} = 230$ volts secondary,
and $y = 230/\sqrt{3} = 132{\cdot}9$ volts,
then $x = 3y = 132{\cdot}9 \times 3 = 400$ volts $= AB$.

For maximum economy the primary h.t. should be connected in *star*; for maximum flexibility and adaptability the primary is usually connected *delta*.

Note.—The equilateral figure in the "*Z*" vector shown on the left simply represents the neutral point of the three windings *a'*, *b'*, and *c'*, which are tied together and earthed as shown.

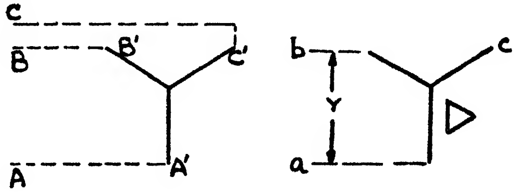
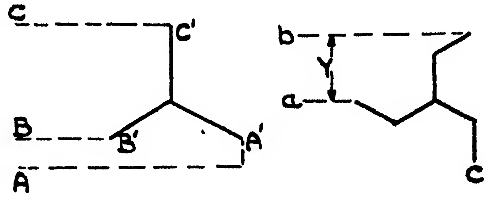
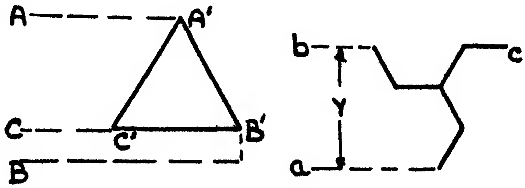
Sometimes standard three-phase transformers are connected in *star* on the high-tension side, and on the low-tension side either in *star* (if the neutral is to have practically no load) or in interconnected-*star* (if it is required that the neutral shall carry load). This latter combination is handy for distribution work because a 400-volt *zigzag* (interconnected-*star*) connection can also be run with a 230-volt *star*-connection, or *vice versa*, on the same secondary. With the *zigzag* ("*Z*") connection it is practicable to take a single-phase load from line to neutral on the low-tension side; the neutral may also be earthed without causing any third harmonic voltage trouble; hence the reasons for using this connection for distribution work (see fig. 16). However, the disadvantages are: a greater percentage winding is required in the interconnected-*star* winding and the efficiency is less compared with an equivalent *star* ("*Y*") winding; also there are more connections to make and more materials, etc. are required. This connection is rarely used because the *delta-star* (or the *star*-"*A*") bank is the better method of the two and will accomplish the same purposes without the disadvantages, and is preferable in other ways to the *star-zigzag* connection.

The *star-star* connection from an operating standpoint is not so satisfactory as the *delta-star* or *delta*-"*A*" or *delta-delta* or "*Z*"-*zigzag*. With a three-phase *star-star* core-type unit, only approximately 10 per cent. unbalance of single-phase load is permissible without an appreciable drop in voltage on the maximum loaded phase. If the unbalance of the single-phase loads is less than 10 per cent., the transformer will operate satisfactorily on a three-phase four-wire earthed-neutral system; with this system the greatest danger and uncertainty is with a line to earth fault.

When a line to earth short-circuit occurs on an isolated neutral *star-star* bank of transformers very little current will flow (not much more than the exciting current) from the two sound phases, which latter are stressed to 1·732 times the original stress. The current will be too small to operate the relays and clear the fault. Installing a three-phase *delta*-tertiary winding, as shown in fig. 17 (*a*), will serve to supply current for the positive action of relays, etc. The "*A*" system overcomes this disadvantage.

With all its disadvantages the *star-star* connected system offers two important advantages, namely: a transformer with a fewer number of turns of greater current-carrying capacity for a given line voltage, and a fixed lower average voltage to earth. The *star*-connected transformer winding, or a group of three single-phase windings connected in *star*, need only be wound for 57·7 per

Fig. 17.—Showing the common Three-phase Transformation Systems (without the neutral connection for use on the system) available for *unequally* balanced loads on the

Primary.	Secondary.	(Primary.) (Secondary.)	
A=0·866I A′=0·866I B′=0·577I C′=0·577I B=0·577I C=0·577I	*a*=I′ *b*=I′ Y=*load*		(*a*)
A=0·866I A′=0·866I B′=0·577I C′=0·577I B=0·577I C=0·577I	*a*=I′ *b*=I′ Y=*load*		(*b*)
A=I B=I A′B′=0·866I A′C′=0·577I B′C′=0·577I	*a*=I′ *a′*=I′ *b*=I′ *b′*=I′ Y=*load*		(*c*)

(The *star-star* connection is shown here with an auxiliary winding; *delta*-connected in the secondary.)

cent. of the voltage required in the *delta* system. The average voltage to the neutral from all points of the windings is 50 per cent. of the voltage from line to neutral, while that of a *delta* is 69 per cent. The product of the turns times the average voltage to neutral with the *star* connection is only 41·8 per cent. of that for the *delta* connection. The windings of a *star* have 173·2 per cent. the current-carrying capacity of the windings of a *delta*. There need be only one terminal per phase for the *star* as against two per phase for the *delta*. With the *star*, if a spare unit is required, whether single-phase or three-phase, it is cheaper and requires less wiring and the connections are simpler than in the case of the *delta*. The maximum voltage on line insulators is also fixed at a maximum of 57 7 per cent. of the line voltage for the *star* as compared with the *delta* connection. It is possible with the *star* to maintain polyphase service at a substation or on a branch line with only two conductors in the event of one conductor being cut out, or broken and disconnected—this cannot be done with the ordinary *delta* system, but the "*A*" system may overcome the disadvantage and also provide that the whole system shall be earthed, which is a very desirable practice in cases of necessity which may arise on industrial installations, etc. When a conductor is down, whether with *star* or *delta* system, this is instantly detected on the *star* and "*A*" systems with earthed neutral, but not on the *delta* system with isolated neutral or without a permanently earthed phase, and, as important loads are generally served by two circuits, or are in a loop, service is not a hazard and is only momentarily interrupted in the case of the *star* or "*A*" system. There is a total absence of arcing earths (which cause breakdowns of insulation) on the *star* system with earthed neutral and on the "*A*" system, but not on the isolated *delta* system. For the "*A*" system there is no likelihood of a sudden shifting of the static neutral, which would bring additional strains on the system insulation. With the *star* and "*A*" systems any danger is confined entirely to the point of failure, whereas dangers are generally increased on the isolated *delta* system. The location of a fault in the *star* and "*A*" systems is easier, which condition alone is a very important advantage in practice.

Judging from the various points given above, it is not difficult to see how flexible, adaptable, reliable, economical, and useful can be the *star* and the "*A*" systems, especially the *delta-star*, *star-delta*, and the *delta*-"*A*" or "*A*"-"*A*" or *star*-"*A*" connections, remembering that a true neutral point is available for the *delta*-"*A*" connection, as shown in fig. 13. For general distribution work

these two different transformer connections, *i.e.* the *delta-star* and the *delta-"A,"* can be applied to the best advantage, and may offer a distribution system nearest to the ideal, *i.e.* a three-phase four-wire secondary distribution system with greatest flexibility, etc.

The transmission problem more or less common to the whole world is concerned with the three-phase three-wire system. This is not so with the distribution problem, which is different and requires a close study of the primary and secondary systems. One of the chief requirements is a system which, when judged from every angle, is found to be the best applicable not only for the present but for all time.

Of far greater importance than transmission is the general distribution of electricity at voltages at and below 33,000 volts. Fortunately, this country has settled on adopting a polyphase symmetrical system for the main transmission lines. Having adopted this main transmission system, we become economically limited to the use of one or two symmetrical polyphase systems for general distribution.

In the choice of the best distribution system and best line construction, both of which should always go together, the optimum distribution system and line construction calls for the following features:—

It should represent the simplest system taken in part and as a whole.

The most flexible system for the greatest safety and protection.

The best system for combined light, heat, and power over one circuit.

A system that offers the best, simplest, and cheapest means of starting out with the least possible number of conductors and/or wires, and, when load requirements demand, can be completed with the least expense and least modification, coupled with greatest protection.

A system offering the best possible diversity and load factors.

The safest and best operating and best earning system.

The lowest in first cost whether starting out in part or as a symmetrical polyphase system.

The best system for distribution to remote or scattered areas.

A system offering the best voltage regulation on all phases regardless of load balance.

A system permitting the least conductor clearances to earth.

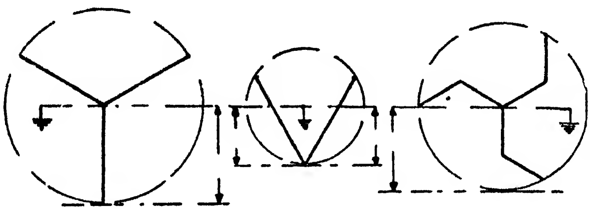
A symmetrical polyphase system allowing the least total sectional area and least number of conductors to deliver an equal kVA.

A system capable of delivering satisfactory polyphase service when one conductor on the line is broken.

A system capable of delivering satisfactory polyphase service when one phase-transformer is burnt out.

A system capable of delivering satisfactory polyphase ser-

Fig. 18.—Showing relative Voltage to Earth for *Equal Total Transformer Voltage* Winding, using the *Star*, " *A*," *Delta*, and " *Z* " or zigzag connections, respectively.



Note.—For equal ratio of secondary turns, the *star* connection provides the highest voltage between phases, and the " *Z* " connection is second highest. The *delta* and " *V* " connections provide the lowest voltage between phases, and highest between phases and earth, but the *delta* offers a flexible, balanced, more adaptable and reliable system. The *delta* and " *A* " connections are specially suitable for the lower voltage systems such as distribution systems.

vice when one line-conductor and one phase-transformer are put out of commission.

A system requiring the least number of distribution transformers and/or the least total transformer kVA capacity for the combined loads.

A system requiring the least number of service connections for the combined loads.

A line construction offering the best means for retaining and maintaining the highest flashover value for a given insulator rating and line voltage.

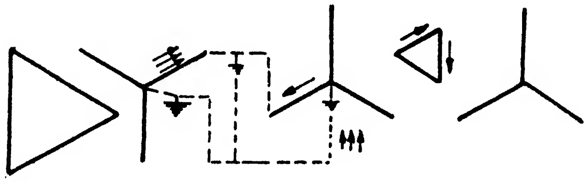
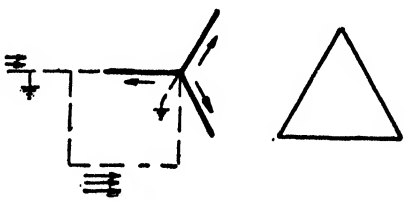
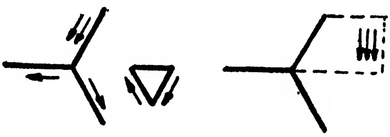
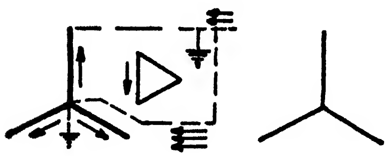
A line construction presenting the ideal outline to resist stresses.

A line construction possessing considerable elasticity to equalise unbalanced loading and/or to throw off or dislodge snow and ice accumulations easily.

A line construction possessing desirable insulating and protective properties.

A line construction and electric circuit offering the best

FIG. 19.—Showing relative Magnitudes of Short-circuit Current for the more common System Connections.

	(Step-up) Transformers.	(Step-down) Transformers.	Short-circuit Current.
(*a*)			$I_s = \frac{100I}{3 \times \%IZ}$
(*b*)			(*Star* primary.) $I_s = \frac{100I}{\%IZ}$
(*c*)			$I_s = \frac{100I}{\%IZ_{,} + \%IZ_{,,}}$
(*d*)			$I_s = \frac{100I}{\%IZ_{,,}}$

Where
I = rated load current.
Z = impedance of one phase.
$Z_{,}$ = impedance between primary and secondary.
$Z_{,,}$ = impedance between primary and tertiary.

Note.—
→ I_s
⇉ $2I_s$
≡ $3I_s$

means for protection from lightning without the use of additional conductors or wires other than the circuit itself for the combined loads.

The two systems that best meet all these requirements and which most nearly represent the ideal for a distribution system, are the three-phase four-wire systems shown in figs. 7, 13, and 16.

With reference to the "*A*" three-phase four-wire system and its conversion from the *delta* for the purpose of operating existing secondary lines at 100 per cent. increase in line voltage, say an increase of from 100 to 200 volts or from 200 to 400 volts, which gives 115 volts from line to neutral in the one case and 230 volts from line to neutral in the other case [see fig. 13 (3)], the old transformers would be operated two in series. That is to say, in the former case two 25-kVA transformers would be hung on the same pole, to supply a load of 70 kVA per 300 yards of secondary line and connected in series on the secondary side. Not only are very good results usually obtained by using two transformer secondary windings in series, but all the old transformers can be used to best advantage in this way.

For l.t. secondary installations, three different methods of earthing are in use, namely: earth the service installation, or, earth the conduit but not the service installation, or, earth the non-current carrying parts of the installation. For this country the latter-mentioned practices are followed—they do not guarantee safety to life. In many dwelling-houses and works there are places where, if an accidental contact were made, such contact would be fatal to the person. The author doubts whether any person could maintain a perfect hand-to-hand contact with any circuit operating at one-eighth the present normal *minimum standard* a.c. voltage of 230 volts to earth, *i.e.* $230\sqrt{2}/8 = 40$ volts *maximum*. These questions of safe voltages, etc., are discussed in detail in Chapter VIII.

CHAPTER IV.

TRANSFORMER SERVICE REQUIREMENTS.

TRANSFORMERS of several hundred kVA capacity and under are generally known as distribution and service transformers, and they are divided into what may be called *distribution* and *service* kiosk, platform, and pole-type transformers. As a whole they constitute the major portion of the central station load, and they give rise to by far the major portion of the hazards because they supply the energy for all classes of electric lighting service and dwelling-house appliances as well as for small and medium-sized motor installations. They usually possess, therefore, a very high factor of safety in insulation strength, so as not to endanger the lives of the millions they serve. Usually they are highly efficient and capable of carrying momentary loads much in excess of their rated capacity; they are also designed to give a high "all-day" efficiency and a voltage regulation well within the limits prescribed by accepted good practice.

Practically every distribution transformer is of the oil-filled (sometimes called oil-immersed or oil-insulated) type. For medium voltages and capacities up to about 100 kVA they are usually dispatched from the factory complete with case (or tank) but without oil. Transformers above 100 kVA capacity and the higher voltage types should (depending on their destination) preferably be dispatched in the tank with oil covering the coils. For foreign shipment, the larger high-voltage (station) transformers are usually "knocked down." Transformers are therefore dispatched in various ways, the method chosen depending upon the size of the unit, the type of tank (case or housing), methods of transportation from the factory to the destination, and convenience in installation.

As the designer endeavours to provide every protection of the coils against moisture, so also the operator should make every endeavour to avoid moisture creeping into the oil and insulation, and he should also see that the high insulating properties of the windings are maintained, and that effective cooling of all active material is kept at such a pitch of perfection that relatively heavy

overloads can be withstood with safety and without any injurious effect to oil, iron, or insulation.

The life of a transformer can be considerably extended by effectively and thoroughly cooling all the active material in which heat is developed, as overheating of certain parts in consequence of inadequate cooling, caused either by poor design or poor maintenance in service, will in time lead to crumbling or cracking of the insulation, with resulting flashovers, short circuits between turns, and other kinds of breakdowns. Absolute reliability in operation, even under severe service conditions such as external short-circuits and disturbances caused by transient voltages, is of paramount importance from the viewpoints of both user and manufacturer.

The efficiencies of transformers range between 95 and 99·5 per cent., and the no-load losses between 0·3 and 1 per cent.; the latter losses are of serious consequence in distribution transformers. On the average, the voltage drop in transformers is between 1 and 3 per cent. at unity power factor, and increases with decreasing power factor up to the value of the impedance voltage.

The best and most careful design, construction, and assembly of the transformer can meet the exacting requirements of safety, reliability, economy of operation, and continuity of service *only* when the user and/or the electric supply company properly co-operate with the manufacturer. There are rules for successful transformer operation just as there are rules for successful transformer design, construction, and assembly. The manufacturer does his part and guarantees his products by the stringency of his tests, and it is up to the user to adhere to the operating rules, such as safe load current in the winding, normal voltage operation, proper ventilation, high dielectric strength of oil, cleanliness, periodical inspection, and so forth.

Before entering upon the questions of unpacking, overhauling, cleaning, storing, and operating transformers, it will be of interest to give a few notes on the trend of modern design of the transformers used for the purposes of stepping-up and stepping-down voltages. Disturbances and troubles from the transformers, or from the lines or cables connected thereto, affect each other and may extend to many different parts of the system. Transient phenomena may occur in transformers due to disturbance in the transmission lines or to switching operations, both of which may subject the insulation to severe stresses.

The end turns of transformers are particularly endangered by steep wave-fronts induced on the lines which penetrate into the transformer windings and result in very high voltage differences

between adjacent turns. Therefore, inadequate or badly maintained insulation will either lead to flashovers or/and breakdowns. These incoming pressure waves not only affect the end turns, but, in consequence of reflection, they may affect the coils situated at the neutral point, as in the case of *star*-connected transformers. In view of this, it is the practice to design the windings of distribution transformers in such a manner that full working voltage can momentarily be withstood between each turn. For higher voltages, up to about 60,000 volts, the insulation of both ends (line end and neutral end) is often reinforced so that adjacent turns can momentarily withstand the full working voltage. For the larger station type of transformers used in conjunction with main transmission lines, such as the National " grid " for this country, the insulation of the turns is so amply dimensioned throughout that the turns can endure the full phase-voltage between adjacent turns. Two methods of effecting this are in use, one being that of equally distributed insulation; the other involves the insulation being proportionately reduced in strength all along the winding from line to neutral.

It is well known that reflection can start from the neutral point and thus affect that part of the windings sufficiently to damage insulation and burn free the neutral connections. Equally distributed insulation strength along the winding from line to neutral offers the advantages of minimising or completely cancelling out the possibility of axial short-circuit forces, due to the symmetrical distribution of the ampère-turns alongside the limb, which is the same for high-tension and low-tension windings; this is a desirable advantage. Furthermore, the dielectric capacities of the turns are all of the same value and the whole winding is rapidly charged, so that average differences between parts of the winding are reduced; the charging capacity is reduced when the starting turns are too heavily and disproportionally dimensioned. It is also the practice to install split rings on the first and last turns of each limb; these are of flat copper or brass, with well-rounded corners. They have the same radial width as the high-tension coils and are situated immediately above these coils (for the line-end or start) and immediately below (for the neutral). They fulfil several important functions, a few of which are: they increase the mechanical strength of the high-tension windings; they prevent brush discharge; they provide simultaneous capacitative charging of all the turns of the line-end coils and the neutral-end coils.

With regard to the general arrangement and bracing of the coils of transformers, it has long been recognised that these matters

have a material influence on the reliability, safety, and continuity of service of the transformer. At any time there exists the possibility that the windings may be subjected to severe stresses on the occurrence of a short-circuit or short-circuits, when the initial current surges may well be 100 or more times the normal current and when the electromagnetic forces caused by these current surges may be so powerful that a complete breakdown of the transformer may occur if the windings are not adequately braced.

A very common present-day design is the concentric winding. In this form of winding short circuits tend to compress and extend radially the windings situated on the inside and outside, respectively. Coils of circular shape are, therefore, the general practice, as these possess the greatest resistance against radial forces. Due to the assembly, and to certain heavy current disturbances in actual operation, axial forces do occur in concentric windings; this is especially the case where the primary and secondary ampère-turns are not symmetrically distributed in an axial direction along the length of the limb. The windings should be rigidly braced from each other and the core should be securely held together by clamping plates and firmly secured to the yokes. In the larger type of transformers the high-tension windings are usually subdivided into a large number of small part-coils, which are arranged to take over the weight of the coils, as also the short-circuit forces occurring between part-coils, and transmit these to the supporting structure and thus to the clamping plates for the windings which are secured to the yokes. In this arrangement the relative position of the high-tension and low-tension windings is kept unaltered, even after prolonged service. With certain methods of construction and arrangement, the high-tension windings are often liable to shrinkage; this condition is the starting of trouble, as a heavy short-circuit may cause the coils to become further distorted, which may result in a complete breakdown of the transformer.

The switching out of large portions of the winding on one side of a transformer to obtain different voltages by means of tappings is another cause of distortion of the windings. This should be obviated to avoid and prevent axial short-circuit forces due to the unsymmetrical arrangement and loading of the high-tension and low-tension ampère-turns. The great danger from short-circuit forces is largely minimised by the proper arrangement and bracing of the windings and tappings to maintain symmetrical loading of the ampère-turns.

In all transformers, and particularly distribution or service transformers, the limb and yoke are built up of laminations of high-grade alloys specially treated to reduce eddy current and hysteresis losses to a minimum. Steel laminations are non-ageing, so that there is little or no change in no-load losses after many years of service. The magnetic density is kept low, as this ensures low iron losses and small exciting currents. Each lamination is insulated on one side, and the whole is secured together by well-insulated bolts; in this way the occurrence of short-circuits in the iron, which cause additional eddy currents and consequently overheating of the laminations, is effectively minimised. All burrs on the stampings are (or should be) carefully removed, whilst each individual bolt should be covered with insulating material and, before being fitted, should be subjected to a puncture test to several thousand volts.

Transformers are designed and constructed for a range of characteristics to satisfy central station and electricity distribution requirements for the various countries in which they are to be used. The methods of installation, and the location, operation and maintenance vary but slightly for different parts of the world. Special features may be introduced into the design and construction for certain foreign countries, however, *e.g.* for use in the higher altitudes, for use in extremely cold or intensely hot climates, for indoor or outdoor and pole or vault installation uses, for super-voltage and super-current use, in very large sizes, and in other special-purpose transformers, but transformers are practically the same, independent of their destination or the country in which they are to operate. The purchaser and operator may restrict them to certain guarantees, such as overload capacity, temperatures, no-load losses, voltage drop, efficiency, and so forth; nevertheless, the practical information on transformers as given herein will be found applicable for all countries.

For an extremely cold as well as an intensely hot country, central station transformers are often erected in closed cells arranged along a corridor on the ground floor; the cells are fitted with large doors from which trucks can be run through the corridor, so that the transformers can be easily removed. Where climates are not extreme, all types of power transformers with housings arranged for exposed places may be erected outdoors.

With the ordinary distribution and service transformers it is customary to protect them from external overloads and short-circuits by means of fuses. The medium and large-sized units should have other protective devices so that faults can be observed

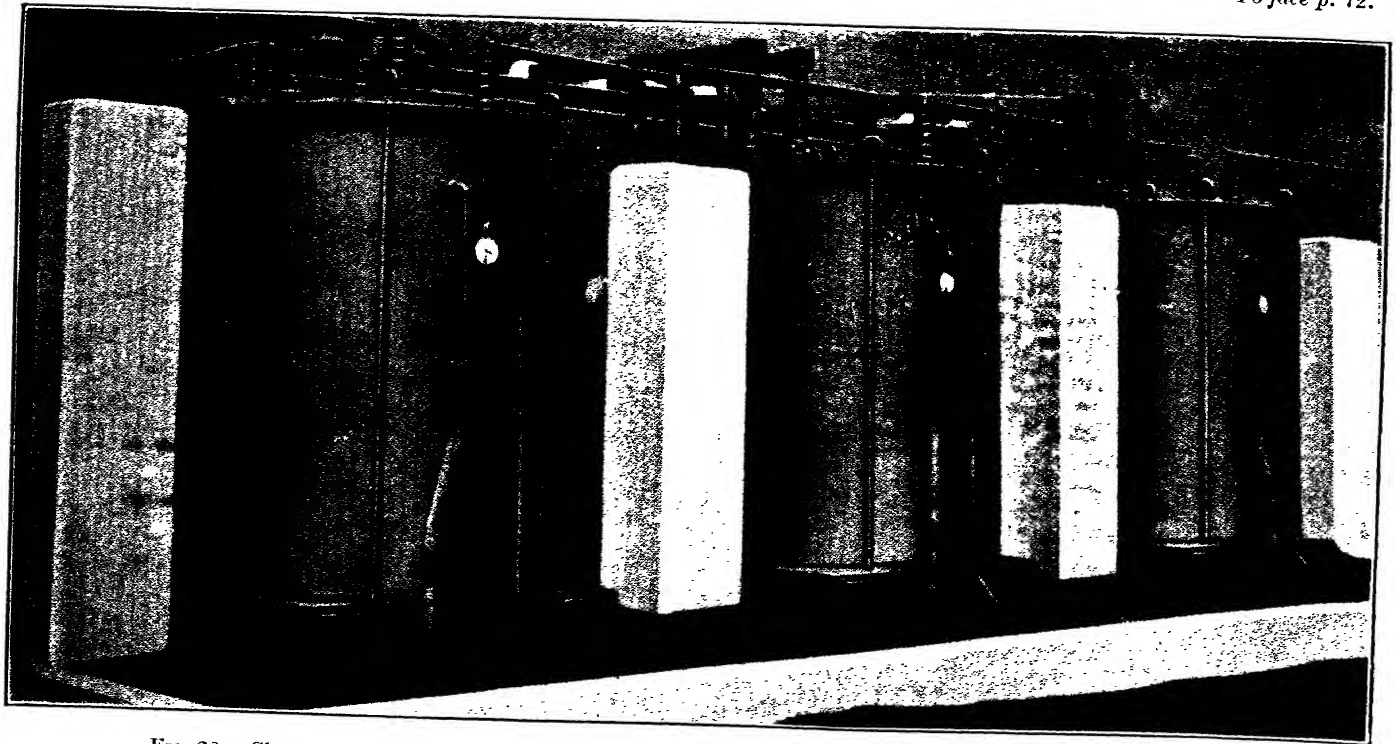


Fig. 20.—Showing up-to-date Outdoor Type, 6000 kVA Single Bank Installation, complete without wiring.

in the initial stages by means of alarm signals or other devices that effect disconnection of the transformer if the disturbance continues. Extensive damage to transformers can be eliminated in this way. Apart from tripping and alarm devices, choking coils are frequently connected in the transformer circuit, as well as arresters, as a protection against transient voltages. As regards choking coils, the opinions of many engineers favour the installation of resistances connected in parallel with the choking coils.

Returning now to the purchaser and the operator of the transformer, who attend to the installation and care of the unit, the first steps are the unpacking, overhauling, cleaning, and storing. Oil-filled transformers should be overhauled before being put into service to see that they have not been damaged in transit. If the core and case are separately packed, all parts should be carefully cleaned and examined after removing the packing material. The transformer may then be ready for drying out, setting up, or storing. During the time the transformer is stored it should be kept in a dry place (whether in the stores or in the station) and should not be allowed to stand where it will be exposed to dampness or to the weather. Before connecting-up the transformer it should be ascertained if the ratio of transformation for which the transformer was adjusted in the factory meets the service requirements. A diagram of connections is usually supplied with each transformer (which is designed for changing over or for several ratios of transformations) so that connections can be checked. All connecting wires and metal straps or bars should be checked for position, and screws and nuts should be inspected and tightened where necessary. The boxes containing insulator bushings or other accessories, dispatched separately, should be carefully stored and thoroughly protected against moisture.

Moisture is the greatest enemy to the insulation, and care must be exercised in handling oil and installing transformers, particularly those wound for the higher voltages. A transformer should not be allowed to stand where it can absorb moisture from the air or any other source, and should not be installed in a damp place. Troubles arising from this and other sources are given in Chapter VII. However, as a further reminder it may again be said that in the handling and installation the careless presence in the transformer of water, tools, soldering fluid or flux, pieces of wire, nuts, screws, or foreign substances of any kind (whether put there by accident or otherwise), or a blow of any sort upon any part of the winding, may cause a breakdown or burn-out.

Every transformer is inspected in the factory, but due to

possible accident and condensation of moisture during transit and storage, the transformer should be thoroughly inspected before installation. If the core is not taken out of the tank, a light should be lowered into the case or tank in order to see that there has been no mechanical injury or shifting out of position due to tipping over, etc. When working in or on a transformer tank or case, with the core inside, all tools should preferably be attached to lanyards of strong twine or other material long enough to be fastened to some point outside the case or tank. In fact every workman should be required to remove from his pockets all loose articles before getting into or on the case or tank and doing work on the inside of the transformer.

When locating transformers, care should be taken that the position presents no undue dampness and that the tank is sufficiently distant from walls, etc. so that condensation is avoided and the heat radiated by the sides of the transformer is readily absorbed by the surrounding air. When erected indoors, the room should be dry and well ventilated. In the case of transformers fitted with an oil conservator, the cover of the conservator should be properly fixed above the transformer cover. For capacities up to about 300 kVA the expansion chamber usually is directly connected to the transformer.

On receiving a transformer from the factory, the windings are sometimes given an insulation test between windings and core; a megger set or galvanoscope or inductor may be used for this. At the same time it may be desirable to make other tests to see whether the coils or other parts of the transformer have become loose. Various instruments are available for making insulation tests. It may be desirable to test whether the insulation has become faulty; also to ascertain if the apparatus has the prescribed resistance. The insulation resistance alters with the effects of moisture. The galvanoscope is a useful instrument for testing and for detecting faulty insulation; the inductor is both useful and flexible because it may be used for measuring the insulation on live or dead d.c. or a.c. circuits and on various kinds of installations.

Before connecting the transformer into service it is necessary to ascertain whether the oil is above the lowest permissible level or reaches the required level in the gauge glass (or the conservator in the case of station units), and whether the cock (in the pipe between the tank and the oil conservator) is open; this cock is closed only when the oil is being changed. The pipe is normally shut off, as it is only used when it is desired to move the position of the oil conservator. In transformers without expansion

chambers, relief cocks are placed on the cover of the tank; these are always left open.

An oil-cooled transformer, whether for station or distribution service, requires no attention during operation. In fact it is a common saying that distribution and service transformers are installed and then forgotten, no attention being given to them until something happens. Although reliable to a high degree, several things may go wrong; these are mentioned in Chapter VII. To avoid many of the service troubles, distribution and service types, as well as all other types of transformers, should be given periodical inspection. This ordinarily consists of an examination of the tank, terminal board, leads, and oil. The oil-level should be noted and a little of the oil drawn from the bottom of the tank and tested for moisture; if appreciable, the water can be seen in the bottom of the vessel. Always, when in doubt, the sample should be submitted to a dielectric test (see p. 78). Apart from the possible presence of water in the oil, a sample should be drawn off from time to time from the bottom of the tank and the degree of cloudiness ascertained. At least once every year it is advisable to open the tank and to free the oil and the transformer from oil sludge, if any. With some transformers of the heavy-duty type, no matter how satisfactory their operation has been, it is advisable to open them up and subject them to a thorough inspection once or twice a year.

Self-cooled oil-insulated transformers (which is the general type for distribution work) depend entirely upon the surrounding air for carrying away the heat. For this reason every care should be taken to provide proper ventilating facilities. If installed indoors, the unit should be so placed and so ventilated that the heated air can readily escape and be replaced by cool air from outside the room. If the room is badly ventilated, there is small chance of this exchange of air properly taking place and the temperature of the air in the room may become excessively high. At a given load the temperature of a transformer will be a fixed number of degrees above the temperature of the surrounding air, and as the temperature of the air rises, the temperature of the transformer is also raised in equal amount. For this reason great care should be exercised to provide a room sufficiently well ventilated to permit the operation of a transformer at a reasonable temperature, which will always be a few degrees higher than that of the surrounding air. Self-cooled transformers should always be well separated from one another and from the walls in order to permit free circulation of air around and about the cases; their

separation from the walls and from each other should not be less than 2 ft., preferably double this. When in position, the oil gauge and thermometer should be in full view.

As a general rule, the temperature of the surrounding air should not exceed 35° C. The highest permissible temperatures for transformers, based on the maximum temperature *rise* above room temperature, are approximately:

50° C. for unimpregnated windings insulated by fibrous material;
60° C. for impregnated windings insulated by fibrous material;
70° C. for oil-immersed.

These temperatures are calculated from resistance increase measurements. They are applicable to the heating limits for drying-out, under short-circuit tests, and operating at overload capacity. For instance, as regards the latter, depending on the type of transformer and the time of the year (winter or summer), the same maximum temperature and heating limits may mean an overload of from 30 to 100 per cent. for one or more hours daily for several weeks during the year (this is especially important during the winter months). The temperature of the windings can be determined by their increase in resistance, using the following formula:

$$T = \frac{R' + R''}{R''}(235 + t'') - (t' - t''),$$

where

T = increase in temperature, in °C.;
R' = resistance of the winding hot;
R'' = resistance of the winding cold;
t' = temperature of the cooling medium;
t'' = temperature of the winding cold.

It is important that the measurements of the resistance increase be made immediately after switching off the current.

Water-cooled transformers are essentially station transformers. They depend almost entirely upon the flow of water through their cooling coils for the carrying away of the heat, so that the temperature of the surrounding air has little effect upon that of the transformer. For this reason air circulation is of minor importance. Thermometers and outlets for the water-cooling coils should be on the front side so that abnormal temperature or failure of the water supply can readily be noted.

Due to the fact that transformers are so very substantial and reliable in service, there is a tendency to assume that all that is

necessary is to maintain the oil at the normal level and to avoid exceeding the temperature limit. Reliability requires that all parts of a transformer, especially the high-tension insulator bushings, shall be kept clean by wiping as often as conditions require. This is important, as dirt and moisture are the two principal enemies of insulation; sound high-tension insulator bushings have been known to fail simply because of the accumulation of dirt.

Oil gauges should be kept clean and in working order, and should be plainly marked to indicate the limits within which the oil must be maintained. For station types of transformers the oil-level in the tank should be noted several times every day and the lowest level noted and entered, together with the highest temperature, in the station log sheet. For good and safe operation it is necessary at periods to ascertain that the dielectric strength of the oil is maintained at a high value. The most common cause for decrease in dielectric strength of transformer oil is the presence of moisture or water. As regards the former, owing to the breathing action which results from the expansion and contraction of the air above the oil in response to temperature changes caused by variations in load, particularly in a damp climate, moisture may be drawn into the tank through any opening, then deposit and mix with the oil.. To avoid this action, various devices are used. It is really a manufacturer's problem, but the operator is depended upon to seal cases and tanks properly. The operating engineer must not be content with simply knowing what has been provided; he must be fully alive to the fact that some kind of breather containing an anhydrous material must be provided and that openings must be avoided; hence he uses quicklime or calcium chloride to abstract the moisture in the air entering the transformer tank. In the various conservator methods, periodic inspection for leaks, cleaning, refilling with chemicals before the charge is used up, drawing-off of water, etc., are all essential to good operation and maintenance.

When a transformer is first placed into service, air is present above the oil in the tank. When the load on the transformer increases, its losses increase and the oil and gas in the space above the oil tend to expand, due to the increase in temperature. With the "Inertaire" transformer installation the air initially present is blown out by compressed nitrogen from a cylinder, and after the air has been removed, the "Inertaire" equipment prevents further entrance of oxygen through breathing action. The breathing regulator does not ordinarily prevent the escape of gas from the

tank until the pressure in the gas space becomes approximately 5 lb. per sq. in. If the rise in temperature is such that this pressure is reached, the excess gas escapes through the breathing regulator and the "Inertaire" compound containers. When the transformer cools down, the reverse action takes place. If the oil and gas contract and cool to such a degree that a slight vacuum is obtained in the tank, the breathing regulator admits gas and makes up the deficiency, as in ordinary breathing operations; in this case the air from the atmosphere comes in through the dehydrating and oxygen-removing materials and is deprived of the deleterious constituents of the ordinary atmosphere, *i.e.* deprived of air and moisture.

The characteristics of transformer oil are, as a general rule, left largely with the suppliers, although rules are laid down. These latter state that the oil must be practically free from mechanical impurities; it must be quite clear at 20° C. and must be free from mineral acid; the tar factor of new, untreated oil must not exceed 0·1 per cent.; the content of organic acid must not exceed 0·05 per cent., calculated according to the acid number; the ash content must not be more than 0·01 per cent.; the flash-point must not be below 140° C.; the fire-point not below 150° C.; the specific gravity must not be less than 0·87 or more than 0·93 at a temperature of 20° C.; the viscosity must not be more than one minute at 40° C.; the freezing-point must not be above −15° C.; the dielectric strength must not be on an average below 23,000 volts when tested between 1-in. diameter discs spaced 0·1 in. apart, and only refined mineral oil must be used. The dielectric strength of oil taken from transformers in service must not on an average be below 19,000 volts under the conditions already given; if the dielectric strength is lower, the oil must be renewed or cleaned. Clean oil should neither effervesce nor froth. It is a good plan before using the oil, and where a testing set is not available, to test the oil for its water content by heating a small quantity to a temperature of about 130° C. and note the moisture, if any; there should be no deposit of moisture in the open glass container.

As the dielectric strength of transformer oil is greatly affected by the slightest trace of impurities, particularly moisture, special precautions should always be taken when obtaining samples of new oil or of the oil taken from transformers in service. Oil that will withstand a test of 30,000 volts between 1-in. diameter flat discs, placed one-tenth of an inch apart, will break down across the same gap at approximately 25,000 volts when five parts of water

per *million parts of oil* are present in the oil. Hence the reason why it is extremely important to handle all transformer oil and oil samples with the utmost care—the life of the transformer may depend upon this, and great losses and hazards may result from improper handling.

When taking oil samples from transformers, errors in the dielectric value of the sample are less likely to creep in than when taking the oil from the container; in fact, opening the container, together with exposure up to the completion of the test, may cause enough moisture to condense on the oil to impair the dielectric value and condemn the oil. There may be a very small amount of moisture on the drain valve, hence a small amount of oil should first be run out before filling the container; moreover, the container should be at about the same temperature as the oil. All samples should be taken on a clear, dry day, and the sample should be sealed at once and tested as soon as possible. Glass containers are the safest; they should be thoroughly washed, dried, and heated to a temperature of about 15° C. above the temperature of the surrounding air. When taking a sample from a transformer, the container should be filled to overflowing after warming it with a little oil also from the transformer.

In most cases where transformers have been dispatched from the factory without oil, if of the distribution voltage types and of the solid mass impregnated design, they should be filled with oil and thoroughly sealed and fastened down while remaining in stock, or they should be put into service as soon as possible; the insulation should never be allowed to suffer owing to exposure to the air. Those of the higher-voltage types should always be dispatched from the factory with oil, where possible, and put into service as soon as they arrive; this may avoid the process of drying them out.

Transformers designed to operate at 60,000 volts and upwards should always be dried out. This is best done by drying the completely assembled transformer, *i.e.* drying the core and oil in the tank by means of oil-heating resistances, or by one of the short-circuit methods. When using the oil-heating resistance method, the heaters are carefully lowered between the core and tank until they reach the bottom of the latter, and are then connected to a suitable source of current. The tank is covered with a blanket or cloth to avoid condensation; the lid of the tank is removed during this process of drying-out in order to allow the water vapour to escape. When using the short-circuit method, too much care cannot be taken in its performance, as

great danger may result to the transformer insulation through overheating. The heat (or drying-out) tests are either done by the short-circuit method with oil, the internal heat test, the external heat test, or by the combined internal and external heat tests. The short-circuit method consists in heating the windings and oil up to a high temperature for a limited time under short-circuit with a partial load on the windings. The h.t. or the l.t. windings may be short-circuited and sufficient voltage applied to the open windings to produce the desired safe current; the applied voltage will vary with the impedance of the transformer. Less than 5 per cent. of normal voltage will usually be required to circulate full-load current in the windings. The temperature limits (maximum temperature *not* maximum temperature rise) are usually higher for the smaller-sized units and the self-cooled oil-insulated units, but in no case should the short-circuit current exceed 85 per cent. of full-load or maximum top-oil temperature exceed 85° C. The drying-out process should be continued until oil from the top and bottom of the tank tests to 22,000–23,000 volts between 1-in. square edge discs spaced 0·1 in. apart with the oil measured at maximum temperature for the load and without filtering. A decrease in the dielectric strength of the oil indicates that moisture is still passing from the transformer into the oil and drying should be continued; an increasing or/and constant dielectric strength of the value desired should be shown before the short-circuit run is discontinued. The insulation resistance should be taken in the course of drying; this resistance will vary inversely with the temperature, and for a 10° C. change of temperature the megohms may change by a ratio of two to one. At a constant temperature the insulation resistance will generally increase gradually until towards the end of the drying period, when the increase will become very rapid.

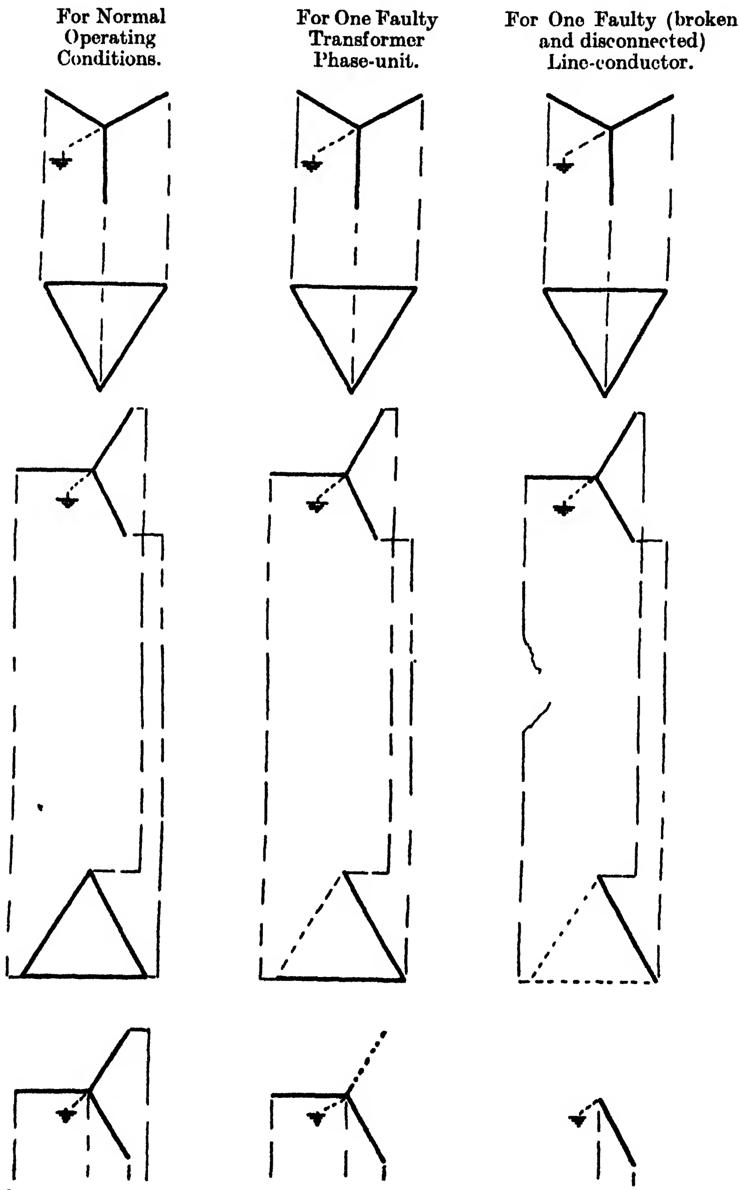
The smaller transformers, up to 50 kVA, are very often erected on poles or structures. This arrangement is not particularly attractive but it has the advantage of cheapness and effectiveness, with maximum ventilation. Sizes ranging from 5 to 50 kVA are erected in the vicinity of the consumers; they constitute what are known as *service* and *distribution* transformers for the distribution of electrical energy over rural areas. These transformers generally have very low no-load losses and show a good annual efficiency at unbalanced loads and they can endure heavy overloads. They are usually provided with tappings, which allow voltage regulation of the network-voltage to within ±5 per cent., so that it is possible to use the same size of transformer either in the vicinity of the

distributing centre, at feeding-points, as well as at greater or intermediate distances from these two said points, and to compensate the drop in voltage, by means of the tappings, as to give an almost constant secondary voltage at any part of the distribution network.

Line voltages supplying distribution transformers are seldom exactly the same on different distribution lines, and for this reason distribution or service-type transformers are provided with percentage taps, by means of which the voltage may be raised or lowered. To enable this to be done, in the past it was necessary to remove the cover which, particularly if it is of cast iron, is very heavy, and the lineman had to support this cover as best he could, while with a screwdriver in one hand he would reach down through the cold oil in the casing to the terminal blocks, in order to change the taps, with the result that often a nut or screw was dropped into the transformer, causing a large amount of trouble before it could be removed. Also, fuse plugs had to be removed, breaking the circuit, before the changing of taps could be attempted, thus causing considerable annoyance to the power users on the line. Altogether it was a hard, disagreeable, and somewhat dangerous job for the lineman. At the present time the change-over from one tapping to another is readily effected externally. Several methods are in use, some of which provide improvements upon the ordinary method of bolting down and fitting of gasket packing between the case and cover of transformers. In the centre of the cover is a small hand-hole cover which also is bolted down firmly with wing-nuts and is equipped with a cork gasket to ensure absolute water- and moisture-proof protection. When the lineman wishes to change taps on the transformer he need not pull the fuses or switch; he climbs the pole, loosens the wing-nuts, drops the hand-hole cover back and turns the exposed porcelain knob so that it points to the voltage on which it is desired to operate the transformer. Dropping the hand-hole cover back, tightening the wing-nuts, and moving the porcelain knob, occupies about one minute for the whole operation of tap changing; no tools are required, the line has not been interrupted, and there is no danger of loose parts falling into the transformer. There is, of course, a possibility of the lineman failing to tighten up the wing-nuts, but, as tap changing is seldom desired, and as the same thing can happen with the ordinary cover not arranged for tap changing, there are advantages in using distribution transformers equipped with external tap changing.

The h.t. side of the step-down transformers is usually without

FIG. 21.—Three-phase System Connections for Normal and Abnormal Conditions of Operation. (With earthed neutral at generator.)



a neutral, and the voltage to earth is not limited. Harmonics are carried through to the secondary load-circuits when a transformer unit or phase-winding breaks down; polyphase operation is thus carried no further than the step-down (and possibly the step-up) transformers for a broken line-conductor. For both these abnormal conditions, residual currents are high and flow from one end of the system to the other. Since generally for two transformations other banks of transformers operate in parallel, a broken line-conductor means a breakdown of the entire system (not one bank only).

Triple-harmonic currents are not carried through for normal operating conditions, but when one transformer or phase-unit fails, or one main line-conductor fails, there are disadvantages in continuing operation. Without the solidly earthed neutral connections on the secondary step-up and the primary step-down transformers, respectively, this system of connection for abnormal operation is no better than fig. 21.

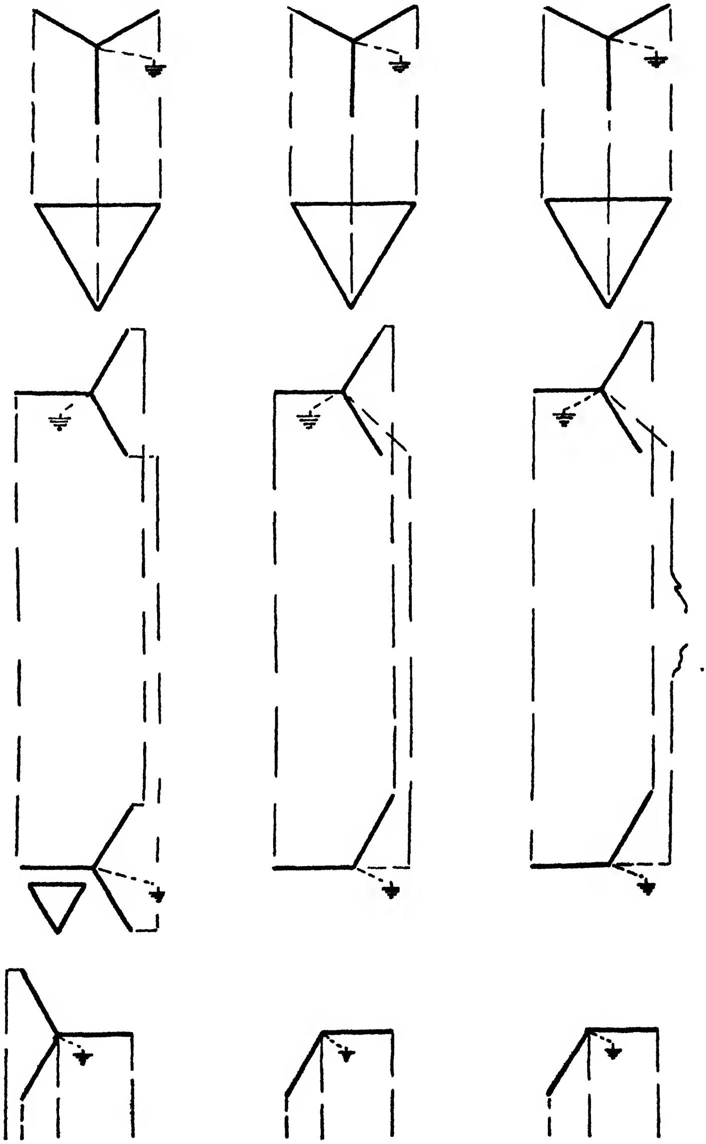
For this system of connections the residual currents are of the lowest values. The step-down transformers cost more, but this disadvantage is more than compensated by limitation of the voltage to earth on both sides. As a spare unit is usually provided, it can in this way be safely and effectively used; otherwise it would be a stand-by and in danger of absorbing moisture, etc. A true neutral is also provided for effective use in case a transformer unit or a line-conductor should become faulty.

If at any time one phase-unit of a bank should become faulty, two conditions are available for polyphase operation on the step-down secondary side, namely: revert to the connection shown by making use of the spare unit for that purpose (leaving the earth connection open), or, if a third winding is used and not a spare transformer unit, revert to the *star* connection by making use of the third winding, changing the earth connection from the middle point to the end at the new neutral point. For a *star* connection on the primary of the step-down transformers the same operating conditions are obtained. This layout of system connections is the most flexible and most reliable and will probably give the best all-round advantages for normal and abnormal conditions.

Main generating station transformers are rarely provided with tappings, since voltage regulation is effected by altering the excitation of the generators. As these transformers serve to step-up the voltage to the value necessary for transmission, the use of the *star* connection on the high-tension side offers several advantages. Where there are no limits as to transport, handling,

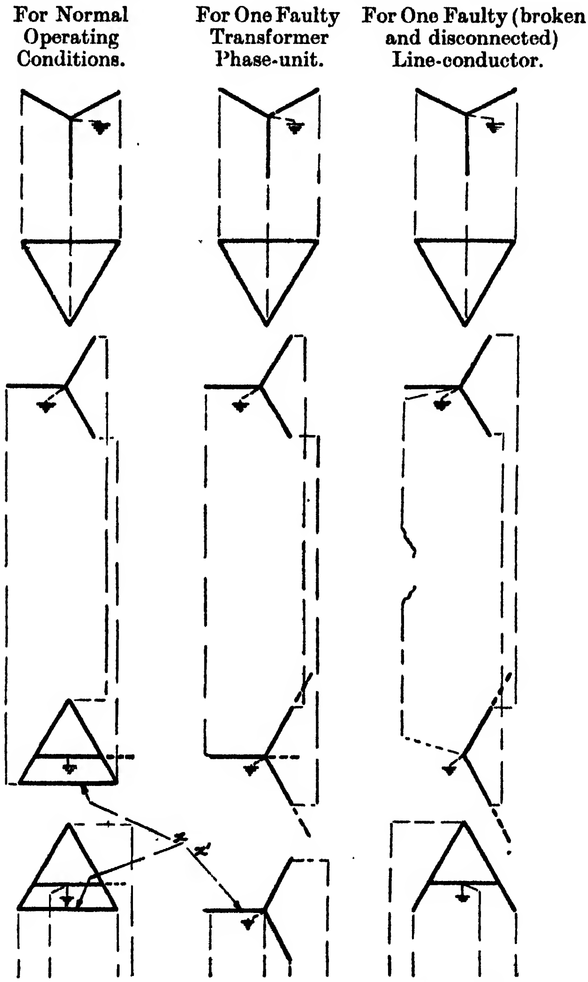
FIG. 22.—Three-phase System Connections for Normal and Abnormal Operating Conditions. (With earthed neutral at generator.)

For Normal Operating Conditions.	For One Faulty Transformer Phase-unit.	For One Faulty (broken and disconnected) Line-conductor.



and erection, the largest sized units are usually the best choice for central stations; their initial cost per kVA capacity is relatively low, their efficiency is better, and the kVA output is not limited

FIG. 23.—Three-phase System Connections for Normal and Abnormal Conditions.



Note.—x is either a third winding or a single-phase (spare) transformer.
x' is either a spare single-phase transformer, or a separate winding.

by constructional difficulties and external or internal cooling arrangements. On the other hand, in choosing a distribution transformer it is desirable always to consider the best characteristics for a given price, or consider the minimum price for a given set of characteristics. With central station transformers the

losses usually come secondary to the price; in service and distribution transformers the aggregate losses are large and are fixed by the costs charged to the undertaking and the transformer kVA capacity.

Substation transformers are often supplied with two 5 or four 2·5 per cent. taps on the high-tension windings; these taps are brought off the middle of the winding in such a manner that the magnetic centres of the high and low are equal, or nearly so. This prevents undue mechanical stress if the transformer becomes short-circuited. The line leads from the windings are not taken to the terminal board. Where taps are taken from one end-coil of station transformers, the asymmetry will, on short-circuit, produce very large end-thrust forces. When a tap to be taken out is large, it is advantageous to reduce the ampère-turns in the other winding opposite the break, not only from the standpoint of forces but also of reactance and stray losses. The general types of distribution transformers are usually supplied with four 2·5 per cent. taps, taken from the middle of the windings. These voltage-regulating taps are usually located in the low-tension winding to avoid the greater cost of properly insulating them for the high voltage of the other winding. In *star*-connected units, tappings are located at or towards the neutral end, but in front of the reinforced portion (if any at the neutral end).

Where fed from a transformer station, feeders may tap any part of the distribution system, or the feeders may leave the station for the purpose of supplying one or more consumers direct. For rural overhead service in general, feeders extend out to various districts where pole-type and other outdoor transformer installations are the rule. The primary voltage can thus be reasonably constant at the distributing centre. For the secondary voltage, compensating devices (see fig. 5) are not always provided for voltage drop, hence the reason for the closely restricted statutory limitation of pressure drop.

Distribution and service transformers come into use where consumers are too great a distance apart for the commercial running of secondary mains when there are relatively heavy intermittent power loads such as would impair voltage règulation on the secondary mains and where there is a large power load such as a factory or works.

For the main stations, there is just reason for assuming that if we build a duplicate main-line transmission for (say) 60,000 kVA, with the line spread over a great expanse of territory, there should exist quite as sound a reason for installing no more than two banks

of single-phase transformers (six units in all) in the receiving station to handle the 60,000 kVA. The six units should be as flexible and at least as reliable as the six conductors; on the other hand, the same cannot be said of the installation of two polyphase units. However, for a distribution network the general conditions are distinct from a main transmission line, as also is the transformer problem, which latter is not concentrated at one point.

As self-cooled oil-immersed transformers are usually designed with exceptionally liberal oil ducts to provide for satisfactory cooling under continuous full-load conditions, the majority of present-day stations and other types of self-cooled oil-immersed transformers can with safety be operated to give from 20 to 50 per cent. daily overloads for many hours by a simple conversion of the tank either to radiator type or water-cooling type, or to both, or to air-jet external cooling with radiator conversion. This may be a desirable change for many station installations. It is most important in the case of three-phase transformer installations uncertain of load growth, where transformers are already in danger of unsafe temperatures due to existing load conditions, where there are no larger spares in stock or no spare unit available, and where it is too costly to buy another transformer.

The problem of selecting the size of transformer to be installed at a given location on a distributing system is simple where the load is definitely established, as at generating stations and certain classes of substations, but the problem becomes more difficult when the transformers are to serve a growing load. The difficulty is greater where three-phase units are installed, because of the moving about of polyphase units, greater capital outlay, stock accumulations, etc.

In choosing the economical size for the most economical operation, it is desirable that we consider possible burn-outs due to overloads, safe operation during the peak-load hours, and the probable growth of the load. There may be a saving due to operating at high load during the peak, but predictions of load growth are very often inaccurate, and it may be more economical to replace transformers to meet increasing loads. It is necessary to take into account minimum yearly charges over a period of years in the question of transformer investment as well as the loading at the time of installation, so that the fixed charges and the losses on the system, added to the cost of replacements by larger units, changes in location and of transformers from stock, will result in the over-all maximum economy. This involves a

careful prediction of load growth and knowledge of the load factor as well as permissible overload on transformer and shape of load curve, etc.

Factors that enter into the calculations of transformer economics are: Cost of power loss in transformers and fixed charges on transformer investments, and cost of power loss in secondaries and fixed charges on investment in secondary copper. If the investment costs of transformers are plotted against transformer sizes, the result will be approximately a straight line for a limited range of distribution transformer sizes. To obtain good economy we may load distribution transformers on the average at about 115 per cent. of their rating at the system peak load. In order to obtain the annual cost of core loss it is necessary to multiply by the total number of hours in the year, whereas in copper loss the annual duration factor must be used. In cases where the system load factor is high, taking transformers out of service during light-load periods may have very little effect on the total losses, since the decrease in core loss may be offset to a great extent by the increase in copper loss due to longer distances of feed. In distribution systems having primary feeder regulators of sufficient range, the average service voltage can be kept normal regardless of the drop in the secondary mains. In such cases the voltage drop in secondary copper can have little or no direct effect on power consumption. In systems equipped with feeder regulators, the voltage at services nearest to the transformers can be maintained at values slightly above normal, allowing services farthest from the transformers to fall slightly below normal. The voltage drop in primary laterals is usually small enough to be neglected. In many distribution systems equipped with voltage regulators, a maximum secondary voltage drop of 4 per cent. is a reasonable allowance; this gives to the consumer a variation from normal of about 2 per cent.

Where transformers are located close together, *i.e.* on adjacent poles or in a vault or a house, it is usual to install a secondary bus for them. If the transformers are loaded to their full capacity and trouble occurs on one or more of the banks, the kVA capacity will be reduced, but the installation of a low-tension bus will permit of selection of the circuit or circuits that may be cut out. On the other hand, if the transformers are not loaded to their full capacity, the loss of a transformer need not require cutting out of circuit. It is of importance to see that circuit-breakers are installed on the secondary side of each bank as well as on each feeder. (See also p. 134.)

For a given service the transformer must not be too small or it will heat up or burn out when the motors are loaded. If the transformers are much too large it means unnecessary energy losses and unnecessary investment. Industrial motor installations are usually rated in H.P., while transformers are always rated in kVA. It is current that heats a transformer, and the power factor must be taken into account. Also, the transformer must supply the losses that take place in the motors installed and operating with the transformers. The approximate relative sizes for transformer and motor installation are as follows:

TABLE V.

RELATIVE SIZES OF TRANSFORMERS AND MOTOR INSTALLATIONS.

System.	Number of Single-phase Transformers.	Capacity per Transformer.	Motor.
Single-phase . .	1	1·0 kVA	H.P.×1·25
Three-phase, 3-wire			
(*delta*) . .	3	0·333 ,,	H.P.×0·31 to 0·39
(open-*delta*) .	2	0·866 ,,	H.P.×0·53 ,, 0·67
(*star*) . . .	3	0·333 ,,	H.P.×0·31 ,, 0·39
Two-phase, 4-wire .	4	0·25 ,,	H.P.×0·46 ,, 0·58

For the different three-phase systems, the relative voltage, current, and transformer rating are as follows:

TABLE VI.

THREE-PHASE TRANSFORMER RATINGS FOR THE COMMON CONNECTION.

System.	Transformer.		Single-phase kVA	Single-phase Rating.	No. of Single-phase Units.	Relative Total Rating, kVA.
	Voltage.	Current.				
				Per Cent.		Per Cent.
Delta .	E	I/1·732	EI	100	3	300
Star .	E/1·732	I/1·732	EI	100	3	300
"*V*" .	E	I/1·732	1·5 EI	173·2	2	347
"*T*" .	E	I/1·732	1·5 EI	173·2	2	347
Zigzag .	0·666E	I/1·732	1·155EI	115·5	3	347

To secure the best operating economy it is essential to keep all distribution transformers loaded nearly to their limit; this limit is defined by the maximum safe temperature and not by the rated capacity as given in the foregoing tables. The limiting output may be the voltage regulation or it may be the temperature rise; in practice it is more generally the latter.

TABLE VII.

TRANSFORMER CAPACITY IN kVA.

(Assuming $\cos\phi = 1$.)

System.	Voltage of Phase-winding. (Primary.)	Voltage of Phase-winding. (Secondary.)	Capacity in kVA.
Single-phase—			
2-wire . . .	E_p	E_s	$2E_sI_s/1000$
3-wire . . .	E_p	E_s	$E_sI_s/1000$
Three-phase—			
Star-star . .	$E_p\sqrt{3}$	$E_s/\sqrt{3}$	$3E_sI_s/3000$
Delta-delta . .	E_p	E_s	$3E_sI_s/3000$
Star-delta . .	$E_p\sqrt{3}$	E_s	$3E_sI_s/3000$
"*V*"-"*V*" . .	E_p	E_s	$\sqrt{3}E_sI_s/1000\sqrt{3}$

For best economy in service it is necessary to know the underloading as well as the overloading conditions of distribution transformers. A transformer may carry loads on the peak with safety, or it may carry only a fraction of the peak load with safety. Proper maintenance and inspection will assure the most economical transformer operation. Overloads can be found by "spot" tests made with portable ammeters during periods of peak or heavy loads, by recording ammeters, by demand indication, by recording thermometers or maximum-indicating thermometers, and by certain danger signals operated either by a given current or at a given temperature; the latter have the advantage of giving direct indication of the high-temperature condition that must be avoided. The knowledge that a transformer is underloaded is not sufficient to determine whether the condition should be remedied or not; it may be replaced by a smaller size unit or it may be kept in place to meet the possible increase of load; in any case, the peak load must be known. If excessive overloads are found, a study is made of the secondary distribution involved, and such additional

transformer capacity is installed as may be required. In cases where a transformer is burned out a careful study is made for several obvious reasons already explained.

Heating is more important in large transformers than small transformers. The heat loss in a large transformer may be forty times as much as in a small unit, yet the total amount of radiating surface in the former may be only four times that in the small unit. Small units therefore do not require any special means of cooling; large transformers do not have sufficient radiating surface, and special surface-forms and area are provided.

In general, single-phase distribution transformers are not banked on the secondary side In districts where the load is heavy and the transformers near together, they are, however, sometimes banked. In such cases it is important to observe that all the banked units have fuses installed in the secondary leads (not including the neutral), that not less than three transformers are banked together, depending on the different sizes (each banked unit should have one adjacent unit equal or greater in size than itself), that adjacent transformers must not vary more than by one standard size, and that the same phase-leads are traced out and all transformers connected to the same primary phase or phases.

In actual installation work the practical man is not particularly concerned with vector diagrams of connections; his way of paralleling is first to seek zero voltages across the switch blades or other convenient known points.

In selecting transformers for parallel operation it is desirable to have them of the same regulating characteristics. It is best to have them of the same make, type, form, series, and size; differences in the impedance voltage are permissible within certain limits to a maximum of ± 10 per cent. Different arrangements of connections may lead to unbalanced phases and make operation in parallel either costly or impossible of accomplishment. Also, for the same arrangement of connections or the same set of bus-bars, satisfactory parallel operation requires the same ratio of no-load transformation and the same impedance voltages.

The relative impedances of transformers will have a large influence on transformer capacities for parallel operation. With unequal impedances, the unit having the lower value will take more current and will reach its rating first. If units are operated in parallel, the total capacity is reached when any one of the component units reaches its limit; the total load cannot be further increased without overloading that particular unit. The capacity

is still further reduced if the units have dissimilar ratios; in this case, not only will the one unit reach its rating before the others but it will in addition carry a circulating current.

If transformers of different ratings are to be operated in parallel, the total rated capacity can be obtained only if the units have the same *percentage* impedance. If two single-phase transformers of 50 kVA output have 3 and 4 per cent. impedance voltages, respectively, the total load is distributed approximately in the ratio of

First 50 kVA transformer	.	50 kVA.
Second 50 kVA ,,	$50 \times \frac{3}{4} \times 100$	$= 37{\cdot}5$ kVA.
100 kVA total rating.		87·5 kVA total output.

On the other hand, if 100 kVA total is to be carried, then the sizes required are approximately

50 kVA $\times \frac{4}{3} \times 100$ . . .	66·5 kVA, first transformer.
50 kVA at 4 per cent. . .	50·0 kVA, second ,,
100 kVA total output.	116·5 kVA total rating.

Supposing there are three single-phase transformers of the following sizes and characteristics:

25 kVA	of	2·5	per cent.	impedance	voltage;
50	,,	3·0	,,	,,	,,
75	,,	3·5	,,	,,	,,

Then the distribution of total load is, approximately

First unit,	25 kVA of 2·5 per cent. .	25·0 kVA	Distribution of load.
Second ,,	50 kVA $\times 2{\cdot}5/3 \times 100$.	41·7 kVA	
Third ,,	75 kVA $\times 2{\cdot}5/3{\cdot}5 \times 100$.	53·8 kVA	
	150 kVA total rating.	120·5 kVA total output.	

Thus, for transformers of equal rating, that unit with the smaller impedance voltage will *always* be the first one to become fully loaded. The impedance method given here is not strictly accurate; for transformers operating in parallel perhaps the admittance method is the most accurate method.

Three-phase units can only be connected to the same circuit on both high-tension and low-tension sides when they have the same arrangement of connections, the same ratio of transformation,

the same impedance voltage, which must not vary more than ± 10 per cent. from the mean, and ratio of outputs not more than about 3 : 1 during continuous operation.

The "*A*" system facilitates all *star-delta* combinations and parallel operations. In seeking three-phase *delta* and *star* polarity combinations it will be found that the following number can be made operative:

12	combinations	for the	*star-star*	connection:
12	,,	,,	*delta-star*	,,
12	,,	,,	*star-delta*	,,
12	,,	,,	*delta-delta*	,,

giving a total of 48 different three-phase polarity combinations for the *star* and *delta* combinations.

When a new transformer is ordered for parallel operation it is necessary to state the conditions referred to above. Standard transformers will work in parallel with each other without any alteration. but they cannot be supplied for different impedance voltages. If the impedance voltages are exactly equal, the load (as already shown) is taken up by the transformers in proportion to their sizes, provided that they are installed near each other. When transformers of the older design (or aged transformers) are to be operated in parallel with transformers of modern design (or new transformers) it is sometimes not easy nor economical to run them together, *i.e.* it is not an easy matter to obtain exact coincidence. If great differences occur, choking coils, the values of which are determined by the resultant of the impedance voltages, can be put in series with the transformer of *lower* impedance voltage. To ascertain if this is necessary, the way the loads are distributed in the transformers with unequal impedance voltages should be calculated, as already shown. Certain polyphase system connections have advantages over others.

If transformers to be connected in parallel are located close together the requirement of equal regulation becomes quite important, and, if the transformers have large current ratings, the resistance of the interconnecting lines may affect the load division to a considerable extent, and it is important to see that the voltage drop to the point of paralleling *is the same* for all of the units. This is important for *delta-delta* connection.

On the other hand, if the transformers are connected in parallel and separated some considerable distance, say 500 yards or more, any slight difference in regulation is usually put right by the impedance of the connecting mains, so that operation will not be

impaired. The unit having the higher secondary voltage will take more than its share of the load; in other words, the transformer having the smallest regulation will take the greatest share of the load, as under increasing loads its voltage will become higher than that of the other units or unit with which it is operating in parallel.

Whether transformers are operated in parallel or not, they should be located as nearly as possible at the centre of the load to be supplied by them and should be so placed that the secondary mains voltage drop is no higher than about 3 per cent.

Some of the conditions which require the parallel operation of transformers at any point are: where the centre of distribution on the section of the secondary main is changeable, due to the varying load conditions of the individual consumers; where the danger exists of placing too many consumers on one unit or bank of units, since the service of all may be interrupted in case of accident to the one unit. The limiting of the number of transformers to be used for parallel operation is usually determined by the relations of the load factors of the individual consumers to the total load factor of the transformers, having in mind the difference in the time of day of the maximum demand of the individual larger consumers.

In connecting single-phase transformers in parallel, it is clear from the foregoing that they must have the same ratio and approximately the same impedance. If both have the same polarity, similar leads are connected to the same line-conductor; if they are not of the same polarity either the high-tension or the low-tension leads must be reversed. The polarity of single-phase units is determined by connecting one high-tension lead to the adjacent low-tension lead and impressing voltage on the high-tension winding. If the voltage measured between the free low-tension lead and the adjacent high-tension lead is less than that impressed on the high-tension winding, the polarity is subtractive; if greater than the impressed voltage, the polarity is additive. Thus, single-phase transformers can be successfully operated in parallel when their ratios and polarities are the same, *i.e.* the secondary voltages are equal in value and in time-phase relation. Either additive or subtractive polarity will cause a phase displacement of zero or 180 degrees.

When placing single-phase transformers in *delta-delta* three-phase banks or groups, it is important to have them of the same ratio, or a circulating current will flow in the secondaries, the value of which will depend upon the amount of unbalanced ratio and impedance of the transformers. If all the transformers are of the

same rating, but the impedances are different, the distribution of the load can be calculated from

$$\text{kVA} = P + P_{,} + P_{,,} = \text{total load on bank},$$

where

$$P = \frac{\frac{1}{\sqrt{3}}\text{kVA}\sqrt{Z_{,}^{2} + Z_{,}Z_{,,} + Z_{,,}^{2}}}{Z + Z_{,} + Z_{,,}},$$

$$P_{,} = \frac{\frac{1}{\sqrt{3}}\text{kVA}\sqrt{Z^{2} + ZZ_{,,} + Z_{,,}^{2}}}{Z + Z_{,} + Z_{,,}},$$

$$P_{,,} = \frac{\frac{1}{\sqrt{3}}\text{kVA}\sqrt{Z^{2} + ZZ_{,} + Z_{,}^{2}}}{Z + Z_{,} + Z_{,,}},$$

Z being the percentage impedance of transformer P,
$Z_{,}$ " " " " P′,
and $Z_{,,}$ " " " " P″.
P, $P_{,}$, $P_{,,}$ are the loads taken by the respective transformers.

The polarity question with three-phase transformers is more complicated than with single-phase transformers. Transformers coming under different groups cannot be operated in parallel with each other on account of the angular displacement, which may be zero, 30 degrees, or 180 degrees. If we desire to determine whether a transformer is connected *delta-delta*, *star-star*, *delta-star* or *star-delta*, and there is no indication from the outside of the tank or case, we can excite the transformer with a balanced three-phase voltage; this may be of low value for the purpose of the test. Assume the high-tension leads to be A, B, and C respectively, and the low-tension leads *a*, *b*, and *c*. Connect A to *a*, read from B to *b* and B to *c*, C to *b* and C to *c*; if none of these voltage readings is the exact sum of the differences A—B and *a*—*b*, the transformer is either *delta-delta* or *delta-star* connected; that is to say, this is the case when none of the readings is either the sum *or* the difference of the high-tension and low-tension voltages. In practice, what we desire to know is whether one winding is *star* and the other *delta*; knowing this, we can then parallel with any other *delta-star* or *star-delta* transformer if impedance and ratio are correct. If in the foregoing test it is found that the voltage readings show either exact sum or difference of A to B and *a* to *b*, the transformer is either *star-star* or *delta-delta* connected. It

should be noted, however, that there is no method of test from external leads to determine if a transformer is *star-star* or *delta-delta* connected unless a neutral or fourth wire or some other lead from the windings is brought out of the tank. If the transformers are connected *star-delta* or *delta-star*, connect A to *a* and read B—*b* and B—*c*; if both are not equal to each other and are less than the applied voltage, read from C to *b* and from C to *c*. If these are not equal to each other and are less than the applied voltage, then connect A and *b* and proceed as before. When it is found that the voltages from B and *b* to both free low-tension leads are equal to each other and less than the impressed voltage, then corresponding polarity relation is indicated.

It is sometimes desirable to parallel a "*V*" bank with a *delta* bank. Assuming they have the same polarity and ratio this can be satisfactorily done, but one leg or phase is the weak point and determines the load that can be taken from the bank without serious overload.

For distribution systems in general, single-phase transformer installations possess the advantage of greater flexibility, easier handling, wider scope of adaptability, greater reliability for the system or circuits because the bulk of faults are single-phase, simplicity of stock, reduced number of units, and much-reduced total kVA capacity in spares, etc. On the other hand, three-phase transformers occupy less space, present a neater appearance, involve more simple wiring, and, for station sizes, should cost somewhat less to install, have a slightly better efficiency, and cost initially somewhat less than an equivalent kVA capacity bank of single-phase units. The two latter form the chief points in favour of the three-phase transformer.

The merits of the three-phase transformer also depend on the system of connections and the type of transformer (shell or core). Independent of the connections, whether *delta-star* or *delta-delta*, a bank of single-phase transformers can give polyphase service when one of the three units fails. With a three-phase core-type of transformer, however, even though the windings are connected *delta-delta*, it is impossible to operate when one phase becomes short-circuited; if, however, the faulty windings are taken out or open-circuited, and no spare coils are available, the transformer can be operated in open-*delta* on both sides, giving the same results as the two single-phase transformer method. On the other hand, whether of single-phase or three-phase design, a *star*-connected shell-type of transformer cannot be operated with one phase damaged, except where the neutral is earthed (in this case the

damaged windings are treated as already mentioned for the core type). We thus see that the system connections favour the "*A*" for both conditions, or the *delta*-connection for one and the single-phase unit for the other.

The merits of the three-phase transformer as compared with the single-phase transformer for distribution systems in general more or less cancel out for the best system connections—decidedly so where the *delta-delta* connection is used. The difference in both cost and efficiency applies chiefly to the larger sizes most uncommon to distribution systems. As the three-phase transformer only shows its chief merits when designed for *star-star* connection, it has little in its favour in view of the fact that the *star-star* system may be subjected to greater disturbances from harmonic voltages and currents than the *delta* or the "*A*" system; furthermore, unbalanced loads cannot be carried on the secondary mains of the *star-star* without the primary neutral conductor or the introduction of a *delta*-tertiary winding. A *delta* is a most valuable connection on any system, and it is accomplished at a minimum of expense, with simplicity, flexibility and adaptability, by use of the "*A*" connection; in this system, the usual *delta*-tertiary winding is not required and the *star* system is retained as well as the *delta* for combined light and power service. The "*A*" system bridges the objections of both systems (*delta* and *star*) in the simplest manner, facilitates parallel combinations and interconnections of the different systems, the elimination of harmonic voltages and currents, etc.

For rural distribution, two single-phase transformers can sometimes be used instead of three without causing any serious unbalance of voltage or current. Lighting and power may often be supplied from the same circuit, hence, for this reason alone, the single-phase unit has the advantage, and, by adhering to the single-phase unit the number of different sizes and the total number of units that must be kept in stock may be considerably reduced, while the amount of distribution system reserve kVA capacity on hand ready for emergency at the various points of a network can be considerably greater than in the case of three-phase units for the same investment.

Usually, if one single-phase transformer is in trouble it rarely affects the other units in the same bank as compared with the three-phase unit, and the time of service derangement is a minimum due to the smaller amount of work necessary in replacing the damaged unit, while frequently the two remaining single-phase units may be made to carry the *entire* load, or at least 58 per cent.

of the original total kVA capacity, whereas damage to one phase of a three-phase unit usually affects at least one of the other phases, which means that the unit must be disconnected; also the cost of repairing or replacing the three-phase unit is more and the loss of time in restoring service is greater. With the three-phase unit the extra cost of replacing transformer capacity is great (three times the kVA capacity is required in the form of *one* unit as compared with the single-phase units), and also reliability is thrown on *one* unit, which has a greater chance of absorbing moisture than the single-phase unit.

A serious disadvantage of the three-phase transformer, largely responsible for its lower first cost per kVA of capacity, is the inherent dependence of one phase upon another through the magnetic circuit. Wherever first cost is not as important as uninterrupted service, it is usually better to employ three single-phase transformers instead of one three-phase transformer. Added to the afore-mentioned advantages, single-phase units also have greater radiating surface, and therefore keep cooler under the same load conditions, and they can be more easily handled, inspected, installed, disconnected, repaired, etc., all or any one of which can be done *without* interrupting the service, by suitable arrangement of the wiring and system connections.

As pole-type transformers are subjected to greater hazards from storms, lightning, heating from the sun, etc., the single-phase type may well be given preference because of the advantages already mentioned, and because the *operating* cost (which often is more important than the first cost) is often in favour of the single-phase unit. Where such hazards are less, as in stations and vaults, the conditions may be different and may favour the three-phase unit from (and only from) the lower initial and installation costs viewpoints. On the other hand, from the costs standpoint a single-phase unit will often afford quite ample reserve kVA capacity for a group of three single-phase units, whereas one three-phase reserve unit would be needed as reserve for a three-phase transformer, which usually more than outweighs the lower costs referred to; the single-phase unit also provides far better inherent cooling, almost in itself a matter sufficient to cancel out the advantage of the improved efficiency of the three-phase unit.

As we approach congested load conditions, which require station installations, the three-phase unit finds its best relative advantages simply on those points in its favour already mentioned. But, in the case of distribution over rural or sparsely peopled districts, the single-phase transformer is, as a general rule, the

most suitable and the best. For the three-phase type of transformer, cheaper total first cost and higher inherent efficiency are *the* arguments in its favour, but these two factors should always be weighed against relative reliability, flexibility, adaptability, total cost of changes necessary due to load conditions and other factors governing the single-phase unit.

In order to avoid changing distribution transformers too frequently it is often the practice to install larger transformers than necessary at the start so that the growth in load for two or more years can be provided for. Obviously, no uniform practice can be established for all undertakings, nor even all districts of any one undertaking, but, whatever is done, the single-phase unit is the most adaptable and most flexible, requires the least excess and reserve kVA capacity, etc. It is evident that where the load growth is rapid it will often pay to install slightly larger transformers than necessary at the start; but where the growth is slight, it would hardly be economical to provide for growth in load over a long period of time. In any case, a larger proportionate number of three-phase units, each three times the kVA capacity of the single-phase unit, would usually be required as spares, as compared with single-phase unit (bank) installations.

Single-phase faults constitute by far the majority of faults responsible for disabling transformers, the whole unit being affected in the case of three-phase units. Although the single-phase unit contains a pronounced inherent third harmonic, the amount of iron being greater, it can be worked at a lesser saturation than the three-phase core-type unit. The three-phase core-type of transformer functions as if a high reactance tertiary were in circuit, *i.e.* the triple-frequency fluxes must travel through an air path and not the magnetic circuit provided by the single-phase transformer. Less insulators are required for the three-phase unit, but as this represents simply the difference of one or two more poles or towers in the line, it is a point that can be omitted against the advantages of flexibility, etc. of the single-phase unit, which also may have the same number of oil-switches but more air-break disconnecting switches than the equivalent three-phase unit.

CHAPTER V.

TRANSFORMER INSTALLATIONS AND STATIONS.

THE different types of transformer stations (central, intermediate, distributing, service) or installations can be placed under three main headings, namely: indoor, outdoor, and underground, of the overhead or surface or vault or mining classes. These can be divided into main or other kinds of stations and installations either constructed in totally enclosed or closed or semi-closed or totally uncovered (permanent) stations located under, on, in, or above the ground, either in or/and on concrete, stone, brick, steel, or composite enclosures. The types of transformer stations and installations met with, and their protection, etc., vary somewhat with the system, country, location, and climatic conditions.

Indoor station types may or may not be enclosed in separate (isolated) cells or apartments to eliminate oil fumes or fire from any one unit spreading to other units. When totally enclosed separate cells are employed, care should be taken that each cell is well ventilated, and ample provision is made for oil drainage, etc. Outdoor stations are the result of seeking economy in first cost; they have the disadvantage of requiring to be operated under all kinds of weather conditions, and usually most trouble occurs at the time of the worst weather conditions. The main sphere of application of outdoor stations starts at voltages above 33,000, which voltage necessitates the use of single-phase oil-switches—this is the case independent of the type of station (indoor or outdoor).

The bus structures of outdoor stations of the larger and higher voltage types should preferably be of a material to assist in reducing transient voltages. The exposed earthed structural work should have a very effective earth-wire system, and all exposed earthed structural work should assist in reducing induced voltages. According to tests, as low as one-third voltage is likely when the bus structures are of steel. Depending on the element of danger from induced voltages, several earthed wires should be strung above the lines, leading some distance (several span lengths) outwards from the stations, as these help to reduce the surge impedance and

are effective in reducing the voltage of incoming travelling waves. Reducing the number of discs on line insulators also helps leakage and flashovers. The relation between line insulation and transformer insulation is shown in fig. 32. A reduction in the line insulation on the few span lengths referred to here might reduce the danger to transformers.

The number or/and size of transformer units in a station depends largely on the voltage required, the number of stations handling the total kVA generated, and whether the supply lines are in duplicate or feed from two sources; for the more important stations, a spare unit per station is usually quite unnecessary, and is costly where three-phase units are used. In many of the larger stations, two polyphase units or banks of the same total kVA capacity as three polyphase units or banks would considerably reduce the total cost of such stations and be as reliable (the three-phase unit is the less flexible, etc.).

For rural distribution the pole type of transformer is in universal use. There are also the pillar type, cupboard type, kiosk type, cabin or chamber type, platform type, and various other housing combinations arranged to suit local conditions and the tastes of the different engineers, localities, and countries.

Due to the more general use of outdoor-type stations, attention is drawn to certain dangers, such as those arising from potential gradients on the exposed station layout resulting from thunder-clouds and improper station protection, and potential gradients across the earth surface of the station resulting from abnormal operating conditions and improper design and installation and maintenance of an earthing system.

If we seek to secure the protection of a line from induced over-potentials by installing an overhead earth wire, we certainly must give at least the same amount of protection to an *exposed* terminal station containing very expensive apparatus. This means the installation of a network *above* and *around* the station, tied into a common earthing system, and also tied to the ends of the overhead earth wires for the lines. Well earthed *exposed* steel is likely to be safer than concrete, and it would no doubt be better to have all station equipment mounted on steel than on poorly earthed concrete; for a pole line, however, concrete is preferable to steel. Steel structure may appear unsightly, but a steel structural type of outdoor station provides excellent screening and earthing.

One of the first problems is the choice of sites facilitating economically the best earths, the best protection and other necessary conditions. Preparation, layout, and construction of the ground-area and common earthing system can be quite as important

as the layout of the system apparatus and equipment. For a big station, the layout of the above-ground part is itself likely to prove less important than the combined underground, surface, and overhead parts of the complete installation; as regards the latter, it is at least as important as the overhead ground wire installation of the line. Good design and construction require that everything in, at, and around the station be kept at an approximately zero earth potential.

Where e.h.t. equipment is placed upon specially elevated concrete piers or pillars, it is obviously essential to ensure that: (1) the operators and attendants are at earth potential at all times; and (2) excluding live parts, every part of the station and its surroundings be kept at earth potential at all times. With steel structural design and the concrete design shown in fig. 30, better facilities are offered to attain these conditions. In any case, it is necessary to provide an earthing system so that the ground station area is always at earth potential, *i.e.* a common earthing system should be installed both under and around the whole station area so that the latter is at a uniform and approximately zero potential to earth at all times, whether operating under short-circuit, lightning discharge, or other conditions. Concrete piers can be made to give safe potential gradients, but their use (without overhead earthed wires) exposes the station apparatus, etc. to full atmospheric charges.

Each concrete pillar or pier should be connected by individual copper rods or bars to a bus by the shortest leads possible, and should be brazed, not bolted, thereto, the bus being connected in like manner to the common earthing system; this also applies to all frames, cases, tanks, etc. of equipment and apparatus. Every part, other than live parts, should be connected in this way to the common earthing system. The size of earth bus will depend on the station capacity, number of units, the amount of short-circuit current and the time allowed for this current to flow, as well as the neutral resistance (if any). The overhead earth wire should always connect into the common earthing system, and not, as is often done, be dead-ended to the tower at or near the terminal station. The station lightning arresters, power transformers, switches and other equipment, should preferably have their own earthing bus, but each should be tied into the common earthing system. The endeavour should be to maintain the resistance of the common earthing system at about one ohm. This low value is difficult to secure, and still more difficult to maintain.

The surface and below-ground parts of a terminal station are of extreme importance. Excluding the layout, which is more or less general knowledge, the above-ground part is practically settled

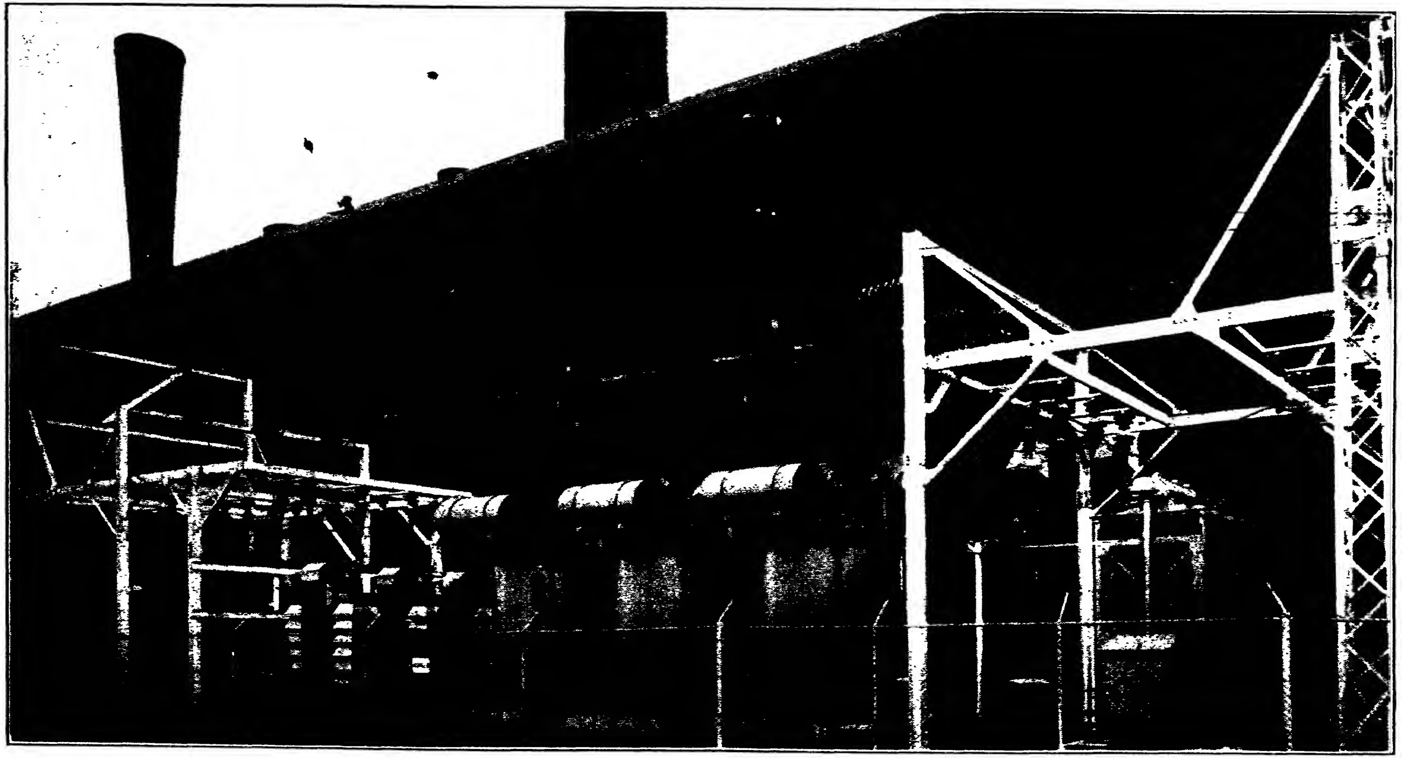


FIG. 24.—10,000 kVA, 60,000/13,200-volt, Single-phase, Oil-immersed, Water-cooled, Outdoor-type Transformers (*Packard Electric Co., Ltd.*)

by the manufacturer, the station arrangement itself being of the simplest type. The insulators and switches (air-break type) may be supported from above or from below, from steel structure or piping or from concrete upright supports. The latter can be made the better practice provided provisions are made for protection from potential gradients above earth potential, and from overhead induced potentials; this is simple, as will be gathered from fig. 52. The below-ground problem has been discussed, and it is suggested that a proper earthing system be installed and maintained. The above-ground problem is no less important, and calls for a protection and screening such that each exposed conductor is shielded from the effects of thunder-clouds and other over-potential conditions, just the same as, or better than, an equivalent length of transmission line conductor.

Over-voltage disturbances are the most prolific source of trouble; nearly all transmission system disturbances occur initially as the failure of some insulator from one cause or another. Short-circuiting a line is very bad, but usually not so disastrous as over-potentials. Earthing the neutral of the system practically eliminates one of the worst dangers, arising from arcing earths; the other most fruitful source of trouble (induced over-potentials) can be minimised by proper design.

For the isolated neutral system, the current flowing in the arc resulting from a flashover may be quite considerable and may subject the two sound phases of a three-phase circuit to severe strain and finally breakdown, or a weakening of insulation sufficient to cause phase-to-phase short-circuit at the time (or any time following) the arcing earth occurs. Flashover of insulators gives rise to an arcing earth, and the earthing of the line in this way creates travelling waves of steep front which are particularly dangerous to apparatus and plant such as transformers at the terminals.

The relative maximum test-voltages for transformers and the lightning flashover values of 10-in. unit insulator-strings for the different standard line voltages range as follows:—

Line Voltage.	Design Test-voltages for Transformers. (kV).	Impulse Flashover.
132,000	270 to 460	1300 to 1700 kV.
110,000	230 ,, 380	900 ,, 1300 ,,
88,000	190 ,, 300	750 ,, 1000 ,,
66,000	130 ,, 230	600 ,, 900 ,,
44,000	90 ,, 150	450 ,, 600 ,,
33,000	60 ,, 115	350 ,, 450 ,,

These insulator impulse flashover values may be used for designing purposes: for instance, 1700 kV are equivalent to 12 units, and 900 kV equivalent to a string of 6 units. Knowing these values and the protective ratio, we may calculate the safe height of line-conductors above ground line for any given transmission line. The question of impulse flashover for the transformer is under investigation; the relative test voltages imposed on transformers is given here for comparison.

Over-potential waves travel to, and rebound from, terminal stations, and such vulnerable points of the system (more than any other) must be designed to take care of disturbances which originate at any point on the transmission line. The terminal points are the first to bear the brunt of reflected waves, hence the insulation is more likely to be weakened (relatively more so than on the line), thus requiring a relatively greater protection from over-potentials coming in and those directly induced on the station. When a flashover occurs, the maximum voltage due to an arc depends on the system, and can be taken approximately as given below:

(1) With the solidly earthed neutral system the theoretical maximum voltage obtainable from line to earth is fixed at . . . . . 100 *per cent.*

(2) With the neutral earthed through a resistance, up to *critical* value, the theoretical maximum voltage obtainable (line to earth) is . . . 250 *per cent.*

Placing resistance or reactance in the neutral is all right provided it is sufficiently low to allow enough current to flow to neutralise the charging current, yet sufficiently high to operate the relays. Transformer insulation will satisfy this voltage rise, as the test voltage is 273 *per cent.*

(3) Where there is some damping of the initial arc (the initial arc being taken at 250 per cent.), the final arc may reach a value of . . . 500 *per cent.*

(4) Where there is no damping, the theoretical maximum voltage obtainable (line to earth) may be . . . . 750 *per cent.*

[For this latter condition the required insulation for an *isolated neutral system would be* 7·5 *times* the normal crest value of the line to neutral voltage. *This clearly points to the necessity of the earthed neutral system.*]

A well-designed e.h.t. transmission system seeks to have the insulation of the whole transmission system on a balanced footing, *with a margin of insulation in favour of the transformers.* It is safer to allow flashover on the line (not far remote) than to allow the over-voltage to travel to the terminal transformers and reflect to double or higher values. Travelling waves caused by disturbances of one kind or another are reflected from the terminals. Although arresters are installed they may not be effective in discharging the over-voltage; where arresters are installed they should not only have a straight connection from the line, but should also have a connection from the transformer terminals, the leads in each case being as short and straight as possible; the arrester should also have a low or no higher than about five ohms resistance connection to earth.

For an e.h.t. transmission system it is advisable to establish an earthed neutral in the power transformers at the source of supply and at other terminal stations of the system, using the *delta-star* connection, or the "*A*" to "*Y*" connection, with "*Y*" connections on the e.h.t. side. With this system of connections the triple-frequency voltage is consumed and cannot flow out on the line, the insulation factor of safety is higher, only one terminal of each phase-transformer is endangered, and hazards resulting from arcing earths are very greatly diminished, or completely quenched, etc.

Conductor clearances and separations are at least as important as anything to do with the line—this also applying to insulation. Actually greater clearances and more insulator units should be allowed in e.h.t. stations. The worst part of an e.h.t. transmission system (66 kV and over) at which to permit flashover is in the outdoor station, because the arc caused by a flash may, with but a slight wind, spread from phase to phase in less time than the best oil-switch can open and clear, *i.e.* in less than ¼ second (these e.h.t. systems require ¼-second opening switches). In actual practice sufficient separation and clearance of conductors and supports against an arc spreading to other phases cannot economically be provided, and the best-known practical solution is to quench the arc by quick- (practically instantaneous) opening switches. These practices help the transformer problem.

Of special importance is the fact that it is the duration of the arc, and not the short-circuit current, which is the danger to guard against, and that the arc voltage is directly proportional to the arc length, this latter being very sensitive to voltage; it is quite possible that the critical arc length caused by a flashover

on a 132 kV system may extend to several hundred feet. Arcing rings and horns help to deflect the arc (in still air), and thus protect the end insulator units. An arc must be cleared almost instantaneously, otherwise the intense heat on the insulator and conductor may cause much damage. The melting-point of aluminium is about 1210° F., and that of copper about 2000° F. ; the temperature of an arc is about 3500° F. As these metals are exposed to the arc it is apparent that the time period from start to quenching of the arc must not exceed ¼ second.

The heavy short-circuit current to earth on an earthed neutral system may be great, but it is far less damaging, and the resulting arc of much less length than with the isolated neutral system under equal short-circuit current conditions, because the arc voltage is less. This gives a more favourable condition for oil-switches than the isolated neutral system. Also, conditions are further improved by working the neutral conductor as part of the transmission system; *i.e.*, a combined overhead earth wire and neutral conductor, preferably insulated from the line supports and earthed at appropriate impedance intervals.

Where the value of the insulation for the combined earth wire (continuous overhead guard wire) and neutral conductor is only one-half that of each line-conductor, the advantage of retaining the relative value of the insulation of wood or concrete poles or structures as against placing in direct contact with the pole, provides for an expectancy of reliability many times greater; this method of construction has repeatedly been recommended by the writer during the last few years.[1]

For a given station, the tapping of any line depends on the amount of revenue that would be secured from the extension and installation, as decided by the engineering, commercial, and operating items involved. To arrive at this figure, or range of figures, by close estimation, the engineer would compute the amount that would be required to be spent on the line (or lines) and station (or stations); he would also insert the operating expenses and figures, preferably giving a range of closest values for varying items; he would then deduct the return on the investment, this latter being the deciding factor as to what can be done when requiring to receive a reasonable return on the capital outlay.

First of all the minimum kVA load or the r.m.s. of average load in kW to be tapped and paid for must be known—the price per unit, etc. being understood; but this does not answer the

[1] *Overhead Electric Power Transmission Engineering*, also *Distribution of Electricity by Overhead Lines* (Griffin).

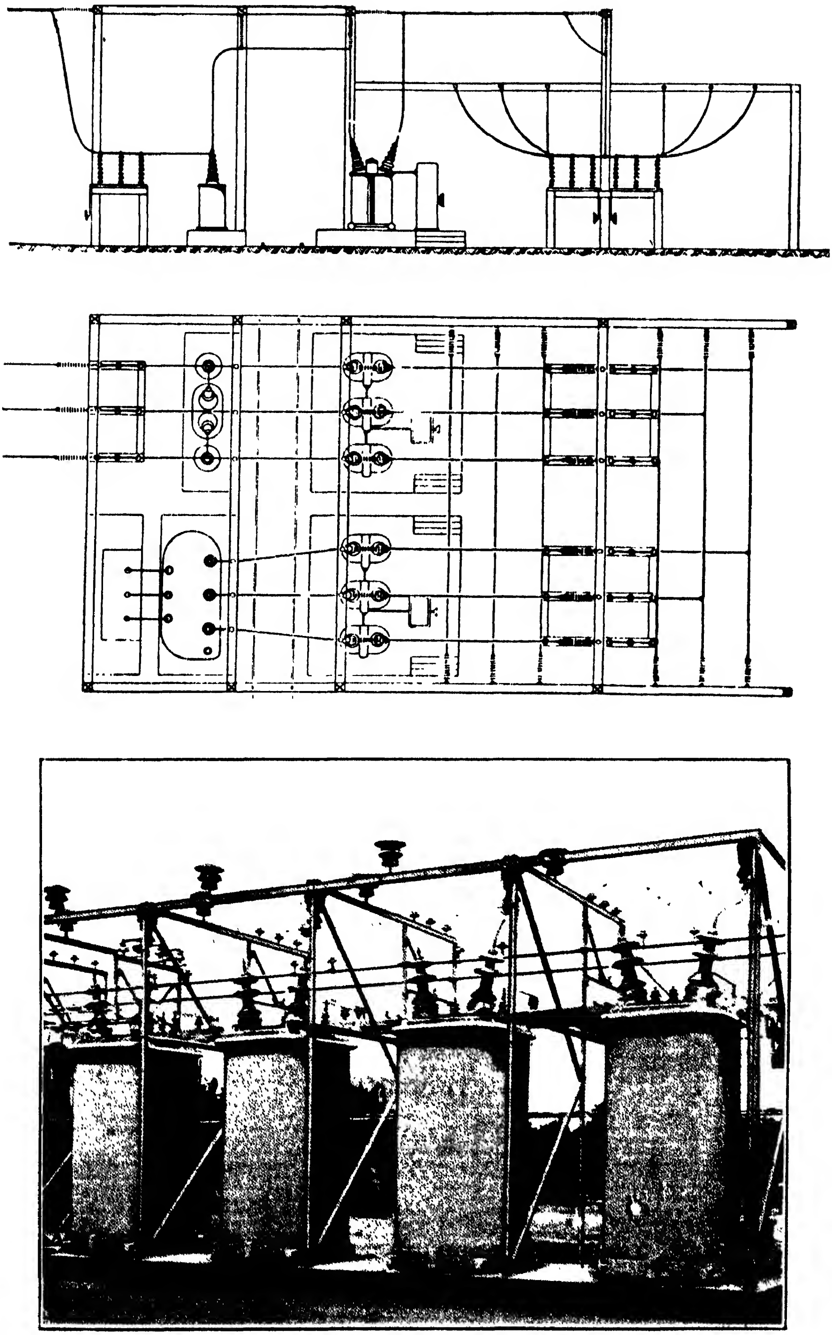


Fig. 25.—Showing Outdoor Types of Transformer Stations with a Minimum Amount of Structural Work.

whole problem. Four or more conditions are possible in connection with any given length of extension and type of e.h.t. construction and design: (*a*) when extending the line and completing the tapping entirely at the expense of the supply undertaking; (*b*) when doing so partly at their expense, depending on the amount the consumer (or receiver) will pay; (*c*) when extending the line or only part of the total installation at the supply undertaking's expense; and (*d*) when doing so partly at the supply undertaking's expense and partly at the consumer's expense, depending on the maximum amount the consumer will pay. The minimum added kVA load for a given line voltage varies with the length of the transmission extension.

Up to the present time, 100 kV to 200 kV lines are entirely used for the transmission of power between generating stations, and between generating stations and large terminal substations at the larger and more important centres of distribution. Ordinarily such lines are not tapped to supply an industrial load unless for (say) a 132 kV line it is in the neighbourhood of 3000 kW and is located in or close to rural territory. The question is rarely a matter of jeopardising the service of the more important stations and towns by trouble in industrial substations interfering with them, for these should give no more trouble than the city substations.

In some parts of the world engineers think of this matter in terms of population, saying they can afford to tap their main 132 kV lines for a city of not less than fifteen to twenty thousand people, or less than this number when there is an extraordinary power load in connection therewith. The author knows of one company operating 140 kV lines tapping for a population of 10,000 people.

As yet, such main transmission lines designed and operated at from 110 kV to 220 kV are not for individual consumers. Experience so far tells us that it is best to serve rural communities or consumers from some adjacent city or town supply, rather than to attempt to tap the lines specially. The author knows of at least one 120 kV line tapping for 2500 kW, also a 140 kV line extension and substation built for and supplying a *maximum* load of 5000 kW; also the case of a 110 kV line extended at part expense of power company and part expense of consumer for a load of 1000 kW. Incidentally, going back over twenty-five years, it may be noted that the author extended 66 kV lines, building and equipping substations for loads of less than 600 kW; and, twenty years ago, built and operated 60 kV river *floating* substations, each for a load of less than 600 kW. The materials, apparatus, and equipment for these 60 kV floating substations travelled nearly 8000 miles

by sea, nearly 2000 miles by railway, followed by several days' transport by road beyond the nearest railway point.

The total costs for the construction of (say) a 132 kV line extension are high, and it is necessary to secure a good load in order to realise a reasonable return on the capital investment made. There are two alternatives, but they have somewhat interrelated solutions.

As we consider best, we may base the estimate on the figures of kW load secured, or we may base it on the return received on the particular investment. We cannot go far wrong when we compute the amount of load that would have to be secured to earn a reasonable return on the amount of money invested. A reliable and simple method for estimating the return on the investment that may result from any extension and tap is given in the following forms:—[1]

Method for Ascertaining Return on Investment from Extension.

Municipality.............. Town.............. County.....................

Physical Data : (1) Length of line..................... Voltage...................

(2) Substation capacity............... Secondary Voltage..........

(3) Wayleave required...

(4) Subsite required...

(5) Give details of alternative construction.........................

(6) Give details of commitments and obligations.....................

(A) Commercial Survey Based on Estimated Annual Business.

	Within 1 year.			Within 5 years.		
	Consumers (number of).	Sales. kW.	Revenue.	Consumers. (number of).	Sales. kW.	Revenue.
Service Classification :						
Industrial power ..						
Commercial power ..						
Commercial lighting						
Street lighting ..						
Residential lighting ..						
Range and appliances						
Total						

Generation with % loss.
Substation demand kW.

[1] Applicable to transmission or general distribution, such as distributing centres, of any voltage.

(B) CAPITAL EXPENDITURE REQUIRED.

	Within 1 year.	Within 5 years.
	£ s. d.	£ s. d.
Purchase of......................................		
,, ,, ... @ £/kVA		
Construction (material and labour) :		
........miles........kV line .. .. @ £/mile		
........miles........kV line .. .. @ £/mile		
........miles........kV line .. .. @ £/mile		
........kVA........kV substation .. @ £/kVA		
........kVA........kV substation .. @ £/kVA		
........kVA........kV substation .. @ £/kVA		
........miles........V distribution .. @ £/mile		
........miles........V distribution .. @ £/mile		

Total, including % construction overhead...........

(C) OPERATING EXPENSES.

	Annual Expenses.	
	Within 1 year.	Within 5 years.
	£ s. d.	£ s. d.
Production @...........pence per kW generated ..		
Primary Distribution :		
........miles........kV line .. .. @ £/mile		
........miles........kV line .. .. @ £/mile		
........miles........kV line .. .. @ £/mile		
........kVA.........kV substation .. @ £/kVA		
........kVA.........kV substation .. @ £/kVA		
Secondary Distribution :		
............Consumers @........per Consumer ..		
New business and capital expenditure at........... per consumer		
General expenses @...............		
Tax and reserve @..........% of capital expenditure		

Total operating expenses ....
Operating ratio ....
Net earnings ....
Return on Capital Expenditure.............................

The above computation should be made as complete and as accurate as possible for every tapping. The amount of revenue from the line extension under (A) is best given by the commercial department of the supply undertaking. The money required for

line and station as estimated under (B) is then given, and the operating department provides the expenses under (C). The return on the investment is then figured so that we have *the* required factor; hence, there is no guess work. The nearest approach to guess work is in the character of the load, which involves the relation existing between average and maximum rate at which power is necessary to meet the demand, costs rising as the load factor decreases.

In computing figures based on the return received from investment, and on kW of load secured, the writer believes the following figures to be conservative for earning a reasonable return on the amount of money invested for the average, substantially constructed, 132–165 kV substation tapping, *when*:—

(*a*) Extending the line only partly at consumer's expense	1000 kW
(*b*) Extending the line, building transformer house and placing the switchgear and transformers, partly at consumer's expense . . .	2000 kW
(*c*) Extending the line only at supply undertaking's expense	3000 kW
(*d*) Extending the line, building transformer house and placing the switchgear and transformer, all at supply undertaking's expense . .	4000 kW

At the present time satisfactory 66,000-volt substations are in operation for smaller loads than 50 kW; 25 kVA tappings are actually under construction. This practice is highly desirable to facilitate economic rural service—there should exist facilities for taking equivalent kVA tappings from the National "grid" secondary 33,000-volt *overhead* lines, *i.e.* for loads of 50 kVA and less. With 33,000 and 66,000-volt underground (insulated) cable systems the rural service cannot compare with that given by overhead lines from the economic standpoint.

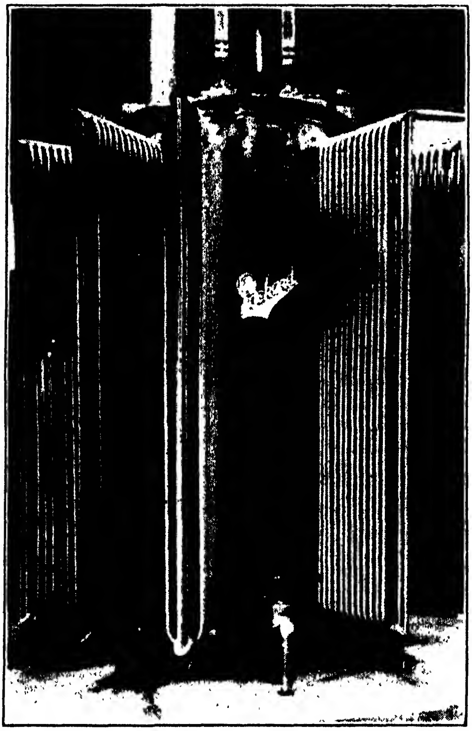


Fig. 26.—Showing installation of a 2500 kVA, 12,000/2400-volt Single-phase Transformer of the Oil-immersed Self-cooled Type. (Built for the City of Winnipeg E.L. & P. Co.)

CHAPTER VI.

TRANSFORMER SYSTEM PROTECTION.

THE protection of the station type of transformer does not necessarily commence at the station or at the transformer. The protection depends on the system design and on the construction and layout of the network (transmission and/or distribution system) located *outside* as well as within the station or stations. If the system is improperly designed, constructed, and laid out, no scheme of protection can quite overcome the handicap imposed on the transformers. Most cases of transformer trouble can be handled by a proper application of modern differential and other current relays, using standard methods of connections, and such relays can be depended upon to disconnect a faulty section of line or a faulty transformer from the remainder of the system, thus preventing a general shut-down or disturbance of the whole system, with its consequent losses; but these can only act most effectively (and be least required) when service conditions have been made favourable.

High-tension transformers are always feeding into or being fed from transmission or/and distribution lines, which are widely extensive and exposed to atmospheric disturbances that cause more or less violent excess currents and over-voltages to find their way into transformers. For the higher-voltage systems, the windings of transformers are designed to withstand with an ample margin of safety more than double the operating voltage. As the over-voltage sources of danger frequently set up pressures much higher than twice (or 2·73 times) the normal voltage, unless proper precautions are taken, they will endanger the insulation covering the copper windings. High-frequency and lightning voltages are the most dangerous transient voltages; they tend to pile up voltages on local parts of the winding (fortunately they do not penetrate uniformly through the entire winding). To make a winding safe against lightning disturbances the insulation strength on a transformer must be greatly increased on its first turns. In actual practice a graded insulation is, as a general practice, used

on the first, second, and/or third coils and sometimes the fourth coil of the winding from the line end, depending on the operating voltage. On certain e.h.t. transformers the insulation on the first of the "buffer-coils" is so heavy that the full transformer voltage may be applied between adjacent turns. It is the first coil that must stand the bulk of the disturbance. As a further precaution a metallic shielding-ring is commonly placed on the top (and sometimes on the bottom, depending on the transformer connections used) of the coil stack, metallically connected to the two ends of each phase-winding; these shields act as voltage equalisers. The shields are also effective in preventing high-frequency voltages at any part of the winding. All the foregoing remarks refer to e.h.t. power transformers of the station type. Distribution and service types of transformers are different, because they are of a relatively smaller kVA capacity and rated for a much lower operating voltage. Nevertheless, although atmospheric disturbances are only slightly reduced, due to a slightly less exposure of line-conductors, the insulation strength of the transformers is much reduced relative to the lightning voltage. Fortunately, the insulation of the connecting lines is of such a value as to permit leakages of a far more numerous and quicker kind than with the e.h.t. long-span lines operating at voltages of 100,000 and above.

From the manufacturer's standpoint, design is studied partly with a view to decreasing the higher harmonics imposed on the fundamental wave. In this respect it is recognised that the single-phase transformer gives a pronounced third harmonic, and that working the iron at high saturation increases the magnitude of the third and higher harmonics. *When* the manufacturer has designed the generator to give a pure sine wave, and a transformer to give the required magnetising current, and with phase-units exactly alike for circuit and bank operation, then the main problems of service can be simplified somewhat.

Depending on the system of connections used, the third-harmonic current can well be carried through several transformations, *i.e.* carried from the generator to the secondary of the step-down transformers. Its presence can be detected from its inductive effect on communication circuits running for some distance parallel to the power lines; the effect is cumulative with the length of paralleling. The effect of residual voltages and currents may increase the normal potential of neighbouring communication circuits and their equipment to a value above earth much higher than normal; transposition of the power-line conductors will not have the slightest eliminating effect on these induced voltages.

It is a rare thing to find two generators of identical wave-form even when both machines give a normal sine wave; there are always minor variations due to tooth ripples, variations in the air-gap and permeability of the iron, etc. In view of these conditions, and the harmonic currents superimposed upon the normal phase currents, it is customary to earth one generator at a time, no matter how many may be installed in a station; it is also customary to earth each machine to the generating earthing bus through its individual earthing resistance; it is also the practice to group machines and earth the largest machine in each group through an earthing resistance. If only one neutral is earthed, circulating currents are avoided, but the neutral of the unearthed machines may rise to a fairly high potential if, due to a fault, the earthed machine trips out. When only one machine is earthed and it develops a fault to earth in its windings at such a position that the voltage is insufficient to pass enough current to operate the relays, the fault will not be cleared and the machine may be badly damaged, but by having more than one machine earthed the chances of a fault current being too low to operate the relays is reduced, as more than one machine can feed into the fault, and so a greater percentage of the windings of the faulty machine is protected. When an earth fault exists on the transmission line, one or more machines are affected, depending on whether one or more generators are earthed and operating; therefore, when only one machine is earthed the fault current will flow in that machine only and may endanger the machine, cause unbalance of loading, cause voltage disturbance of the whole system, and usually trip out the machine. The issue of such conditions, depending on the transmission voltage and the magnitude of the system, may be disastrous as the cause of excessive currents in the first place, then due to arcing earths, causing excess voltage and breaking down the insulation. The danger from losing the generator earth connection is shown in fig. 34.

The generator is usually connected in *star* at the factory and the transformer system connections are decided upon independently. In operation, and for the bigger systems in particular, the endeavour is to maintain balanced loads, avoid unequal leakage from conductors to earth, and maintain equal capacitances from conductors to earth. Without careful system design, construction and operating practice, these desired requirements or the proper co-ordination of power and communications systems cannot be expected. The class of abnormal operating conditions referred to elsewhere, *i.e.* emergency operation when a line-conductor is broken or disconnected, or when a transformer unit is faulty and cut out, would

certainly not be permitted in this country *according to existing Regulations*, but such are followed, and may be desirable, elsewhere, and may be quite necessary for many industrial installations, town supplies, and so forth, and will, no doubt, in instances be employed unofficially in this country; a very important precaution is to be assured of a soundly earthed neutral at the generating station.

As a rough estimate, it is not unreasonable to say that not far short of 90 per cent. of *all* failures on overhead systems are due to faults to earth. In view of this very high proportion of faults affecting transformers and transforming systems, it has long been felt that reliable earth relay protection is necessary to minimise the danger to transformers and/or at the point of fault, also to reduce the duty on oil circuit-breakers, to control inductive disturbances at times of fault to earth, and for other reasons. The methods to be used against this 90 per cent. of the gross troubles depend largely on the system design and its magnitude.

Short lines operating at relatively low voltage, such as distribution systems, can well be classed as distinct from e.h.t. long distance transmission systems; and insulated neutral systems can most decidedly be classed as distinct from solidly earthed neutral systems. At least *four* distinct system arrangements arise in practice, each requiring different methods of protection against faults to earth; these four main arrangements are:

(1) Systems operating with isolated neutral.[1] The symmetrical polyphase systems available are the *star*, *zigzag*, closed-*delta* and "*A*".

(2) Systems possessing very little or no capacity current to earth. This applies to distribution systems in general.

(3) Systems operating with solidly earthed neutral. The systems available are the *star*, "*Z*" or *zigzag*, and the "*A*".

(4) Systems possessing large capacity current to earth. This applies to such systems as the National "grid" for this country.

The danger of discharge to earth for (1) would be due to abnormal voltage rise, especially when coupled with a system such as (4). On the other hand, the danger of discharge to earth for (3) would be due to abnormal current rise, especially when coupled with a system such as (4). As a general rule, the more dangerous

[1] See *Journal of Institute of Electrical Engineers*, vol. lxvii, June 1929, p. 749, which states: "German power-supply engineers have used insulated neutral points principally because of the attitude of the German *postal authorities*, who consider that reduction of the magnitude of earth-fault currents is of chief importance from the standpoint of inductive interference."

and damaging of these two group arrangements is (1) combined with (4).

For the system combination (3) and (4), the design and operating practice is so to lay out the transforming system connections as to fix and reduce as much as possible the maximum voltage to earth, to make the best possible practical use of the whole system charging current to earth for voltage regulation, and for improving the power factor of the whole system, to augment the usefulness of the line charging current by adding synchronous condensers, these also to assist in obtaining system stability, the application of super-excitation of generators, and the use of the lowest possible number of e.h.t. terminals, wiring and other materials for transformers, switches, etc.

For the combination (1) and (4), the design and operating practice is to lay out the transformer system connections for *star* (or *delta* with *zigzag-* or *star*-tertiary winding or "*A*" system, if a neutral point is required), and make the best possible use of reactors from line to earth, or from transformer neutral to earth, so as to choke or neutralise effectively the system charging current to earth during a fault. In this way all the advantages (just mentioned) of over-excitation and use of synchronous condensers with line charging current for improving the system voltage regulation and system power factor and system stability during normal operation would be cancelled out.

For the combination (3) and (2), there would be present those dangers from short-circuits due to earth faults. The heavy current danger to transformers can be overcome by inserting in series with the transformer secondary and the neutral a parallel-series circuit consisting of a reactor and a form of cut-out; during normal operation the reactor will be practically "dead," and no losses will be involved.

For the combination (1) and (2), there are present the dangers from arcing earths due to faults to earth, higher voltages above earth during normal operating conditions, and abnormal induced voltages on the low-tension mains during a primary earth-fault, etc.

For normal and abnormal conditions, the design, construction and layout of the larger transmission systems such as the National "grid" for this country, as also the systems in use over the whole of Japan, Australia, New Zealand, South Africa, and the whole Western Hemisphere, are such as to provide system characteristics and operating conditions that best satisfy the equation

$$\frac{1}{Z}=Y,$$

or $$2\pi f EC + I_c \text{ ampères},$$
where

f = frequency in cycles per second,
E = voltage from line to earth,
C = electrostatic capacity from one conductor to earth (in farads),
I_c = electrostatic capacity current to earth from synchronous condensers (if any installed and operating),
$Z = R + jX = 1/Y$.

Modern design, construction and operating practice in Europe for somewhat similar e.h.t. main power transmission systems are almost diametrically opposite to the afore-mentioned, because the present endeavour is to satisfy the equation

$$I_{,}^2(R + jX) - E_{,}^2(g - jB) = 0.$$

Thus the endeavour is to change the energy from one form into another so that

$$I_{,}^2 L - E_{,}^2 C = 0.$$

But,

$$\frac{E_{,}}{I_{,}} = \sqrt{L/C},$$

and the danger due to the current $I_{,}$ is from the voltage $E_{,} = I_{,}\sqrt{\frac{L}{C}}$.

For any system possessing a capacity charge, the amount of stored energy is equal to $0 \cdot 5CE_{,}^2$, and when a current is flowing through a system containing inductance L, energy is stored equal to $0 \cdot 5LI_{,}^2$. As this energy is obtained from the circuit when the current is started, when the voltage rise producing $I_{,}$ is removed, the energy can be discharged back into the circuit before the current can stop. If the circuit is suddenly opened, as occurs from an arcing earth, a very high voltage may result, keeping the current flowing until this energy is fully discharged. Hence the reason for automatically damping a surge or disturbance by making use of electromagnetic kVA capacity by means of an inductive choke introduced into the system and utilised when (and only when) most needed. One of the disadvantages of this *modern* European system of designing, constructing and operating e.h.t. power transmission systems, is that the dangerous voltage rise cannot be checked in zero time, so that an oscillation of energy is momentarily set up, causing system disturbance; another objection is that of operating the system entirely devoid of direct

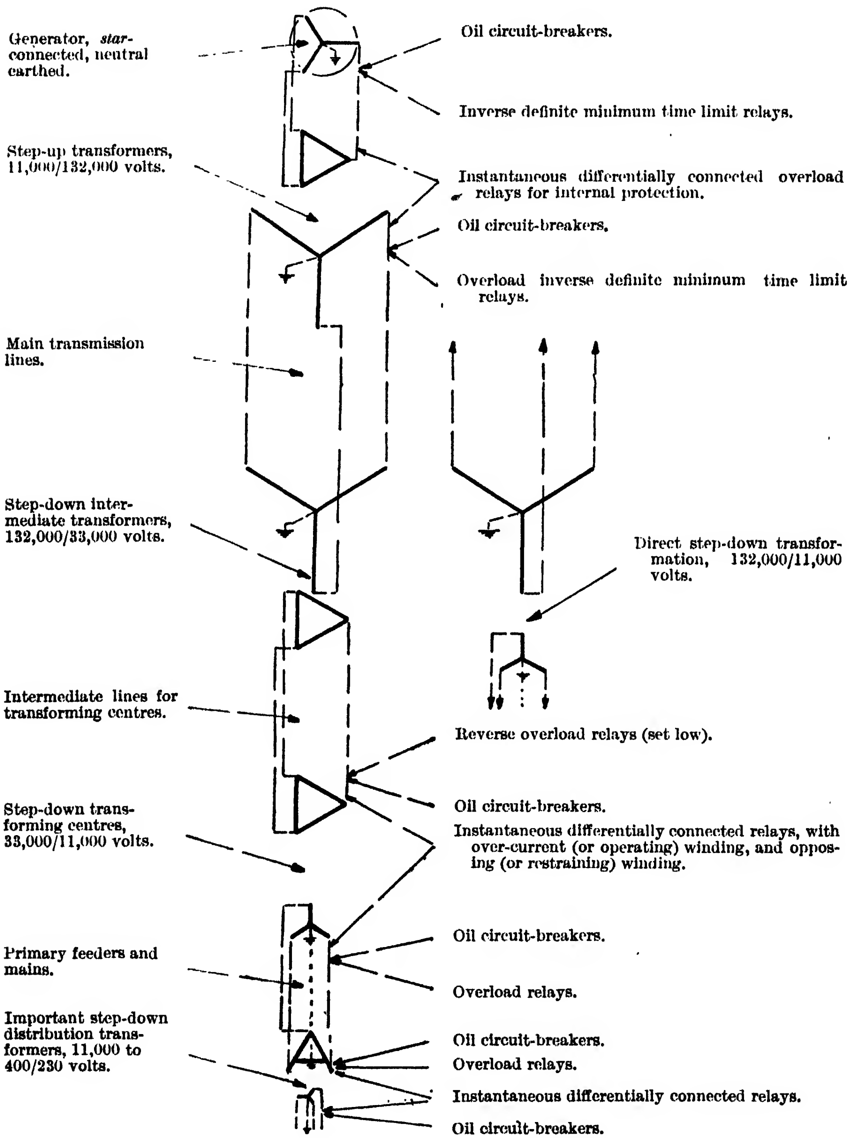
earth connections, a condition which may cause or facilitate very dangerous voltage transformation and phase changing for certain fault conditions, so that three times the line voltage may be induced and maintained on the system (see fig. 42).

While the most eminent engineering authorities associated with the e.h.t. power transmission systems first mentioned in the foregoing are emphatic in their recommendation and approval of their methods of design, construction and operating practice, no less equally learned and experienced engineering authorities are as enthusiastic about and loudly affirm the superiority of the latter-mentioned method. The author desires to add his view that one method can be made as desirable as the other; both methods are therefore decidedly important. For normal operating conditions the essentials of any system should be best efficiency, best voltage regulation, and best power factor improvement. All these (and more) we obtain from the first-mentioned method. For abnormal conditions, which can best be classed as momentary and not operating, we are confronted without a moment's notice with the stored energy in the form of capacity current to earth, which tends to sustain a dangerous arcing earth or/and instability of the system (for e.h.t. systems), whether the neutral is earthed or not. Hence, the essential is to introduce a positive and unfailing means inherent to the transmission and transforming system itself of automatically and suddenly relieving or/and quenching or neutralising the capacity current to earth at, and during, a fault.

Both these distinct methods of layout and operating e.h.t. main transmission systems are first brought about by, and ever afterwards centred around, the transformers connected thereto, which form the most vulnerable parts of the whole system because of the possible complications and suddenly changed transformations arising, which latter depend on the system and transformer connections used, and the possible destruction of the whole system that can occur almost instantaneously.

Certainly the former method, which usually combines (3) and (4) in the foregoing, when properly designed and constructed, is in the right direction in its endeavour to preserve and utilise to its utmost the entire system characteristics $2\pi f\mathrm{EC}$. On the other hand, it may or may not be wise policy to subject the system to instability and severe stresses from line-to-earth short-circuit currents during abnormal operating conditions such as may arise from flashovers or cracked insulators or from broken conductors, when all (or most) of these dangers can be averted by introducing the neutralising characteristics $\mathrm{I}^2(0+j\mathrm{X})$ of equal kVA capacity.

FIG. 27.—Showing typical example of Internal and External Transformer System Protection.



Note.—We may adopt the *direct* transformation (132,000/11,000 volts) or the multi-transformation shown here, and we may have the radial, loop, or the interconnected system. Local conditions and circumstances and future possibilities will decide the number of transformations, the system of connections, number of transforming centres, and distribution transformer and service transformer locations and layout.

This leads us to wonder why we have not to-day (*anywhere in the world*) a system utilising to the utmost the merits of the first-mentioned method for normal operating conditions, and incorporated therewith a method for abnormal operating conditions that only comes into action (for use with losses) when a fault occurs, that is practically "dead" and causes no losses during normal operating conditions, that is automatically instantaneous and positive in action, unfailing in its instantaneous automatic damping-out of the fault current to earth, capable of permitting uninterrupted operation without any (or but little) outward indication of an actual arcing earth or earth fault on the system, that does not increase the "earning" or load-current flowing through the transformers during the abnormal operation, that does not permit of oscillations during fault to earth, that draws and concentrates practically the whole of the disturbance and rush of current upon the inductive winding surrounding the transformer neutral conductor to earth.

The practice of operating systems with isolated neutral is in no small way due to the very general use of the core type of three-phase *star-star* connected transformer; operating with earthed neutral is partly the result of using single-phase units and units of the shell type. Starting with these two different practices, experiences have been built up and knowledge accumulated until to-day we have decided proofs of what is best for each set of conditions. For instance, the triple-frequency phenomenon in the core type of unit can be suppressed by providing a tertiary-*delta* in each transformer. Hence the reason why the views of authoritative engineers are widely at variance on this question. Up till recently this country has closely followed along the lines of European practices, but the question now arises, due to the initiation of the 132-kV practice of the National Electricity Scheme—"Shall we or shall we not earth the neutral point of each transformer? The system, type, and class of transformer in general use are the first considerations and will help to decide this important question most satisfactorily. If power engineers are at fault in their use of types and practices, they may have themselves to blame for the long-standing theoretical decisions and practical restrictions of the communication system engineers and authorities, which restrictions have so far been most costly and detrimental to electrical development, far outweighing, many times, the extra cost of single-phase units or/and shell type of units and their allied practices. With our minimum of 230 volts at the lamp, this question is most vital to the profession and the public generally;

yet it is allowed to be controlled by the communication system authorities. On the other hand, are the power engineers to blame for building up a system so inferior as to be controlled by the communications authorities? If not, why this restrictive control? Why not seek the practice of low magnetic densities, single-phase shell type of units, *delta*, *star* and "*A*" connections, and multiple earthing?

The fact remains that, whatever we do, we should not operate without an earthed neutral system; this means that all systems should possess a true neutral point. There need be no more resistance between the transformer neutral and earth than the straightest copper conductor can offer, but there must be a high reactance when (and only when) a fault to earth occurs. Such manner of protection for transmission and distribution systems in general can be effected by placing in series with the transformer neutral a form of laminated cylinder through which the earthed neutral conductor is run; the laminations would not be closed circles, *i.e.* the magnetic path would have a small air-gap, thus flattening out the flux curve to approach a straight line. If considered more desirable, this form of protector could be shunted by a fuse or relay or other form of cut-out, so that practically the whole current (if any) would flow during normal operation through the cut-out; if the current should reach such a value as to open the cut-out or break the shunted circuit, the inductive protector would be automatically brought into circuit to protect the system against the charging current to earth at a fault. In this way the transformers and lines connected thereto are protected and the fault current to earth is absorbed without placing fault current on the transformers. Moreover, an interruption of service on the occurrence of a fault to earth is rendered unlikely, transformers and generators are not endangered due to unsymmetrical loading, excess voltages can be avoided, and dangers from arcing earths can be made almost nil. Obviously, where over-excitation of generators and synchronous condensers are in use, the desired results are difficult to attain.

In certain cases it may be desirable to place resistance in the neutral. Reactance or resistance may be employed, the former being more effective on systems where capacity current is much in evidence. Whether one or the other is used, it is evident that its value will depend on the system voltage and kVA capacity, and the length of the transmission. Although the charging current in ampères is practically fixed per mile of line (circuit) for a given system and line voltage, the possible accidental fault current to earth is by no means fixed.

For the National Electricity Scheme of this country the charging current of the main 132,000-volt transmission circuit alone is about 0·5 ampère per mile; for the 66,000-volt intermediate transmission circuit it is about 0·25 ampère per mile of circuit. This capacity current should always prove helpful to the system during normal operating conditions, but it can be a danger during earth-fault conditions; the practical requirement is to make good use of the former condition, and make safe the latter condition. If the neutral is earthed solidly there can be no oscillation, and no voltage rise can occur. For this country we have finally accepted the American practice of multiple earthing of the neutral point of the 132-kV "grid" system at all stations.

Excluding those secondary systems where earthing is required chiefly for the safety of the public, it is of interest to note that the maximum permissible resistance in the neutral can, as a general rule, be taken as:

(*a*) Lower for a given voltage and length of line the greater the kVA capacity. (This view has at last been accepted and put into practice by the Central Electricity Board for the "grid.")

(*b*) The longer the transmission line for a given voltage and kVA capacity, the less the maximum permissible resistance or reactance in the neutral.

(*c*) For a given kVA capacity and length of transmission line, the lower the voltage of the transmission system the less resistance or reactance is required in the neutral.

In other words, for each case the maximum permissible resistance in the neutral is limited and varies with the voltage, kVA capacity, and transmission distance.

On the other hand, it is fully recognised that these three views are quite contrary to the European practice of neutralising the capacity current to earth during an earth-current fault, the reasons being quite obvious.

One of the principal questions of protection is to install first that system of transformer connections permitting of the absolute minimum or a total absence of continuous or intermittent arcing at a fault to earth. Prevention is better than cure, and it is usually better to install a system to prevent the initial danger occurring than apply means of any or all descriptions to lessen danger from a dangerous system. The arc, due to flashover of insulator, is often *the* principal factor responsible for so many line-conductors breaking. If an arc is allowed to continue, even for a

very short time (say a fraction of a second), the intense local heat can shatter the insulator and anneal the conductor so that the latter stretches and weakens, and at some future time breaks; thus two distinct breakdowns of service are caused. Arcing earths may produce resonance in the transformer winding—the most dangerous potential stress is between turns of the winding.

An old question now arises, shall we install a reactance to equalise the capacitance of the transmission system to earth, and in this way reduce or eliminate the possibility of either a short-circuit or a dangerous arc when a fault to earth occurs? Or, shall we design, construct, and operate so as to secure a constant voltage system, the best voltage regulation, best power factor improvement, and the highest efficiency for transformers and lines? Both these questions are so interrelated with climatic and atmospheric conditions, with location, and with electrical, mechanical, and economical factors, that a definite and decided answer cannot be given. Also, strange as it may seem, for almost the same general conditions, the highest authorities claim superiority for each distinct method.

When an earth fault occurs on the combined (1) and (2) systems already mentioned, a return circuit between the fault and the transformer may not be established. Such a fault usually extends no further than the secondary low-tension distribution system, and usually is not applicable to the primary distribution system, which invariably responds by a sudden and violent "kick," drawing sufficient current to trip the circuit-breakers. For such systems the arc to earth will produce dangerous excess voltages that can well exceed several times normal voltage, and these serious conditions will endure so long as the earth fault is maintained; also, for such systems (isolated neutral systems) it is important to bear in mind that a relatively small current flow to earth will maintain an arc, as also will a relatively low voltage to earth. However, the excess voltage produced (and piled up) on such systems is very dangerous to the insulation of the whole transmission and transformer system, and may cause its breakdown at a place far remote from the actual fault.

There are two general classes of troubles arising in the systems themselves, due to the particular line construction and the transformer connections used. These troubles are those from excessive currents and those from excessive voltages. The former produce mechanical stresses and overheating, while the latter often break down the insulation on one or more parts of the system. The mechanical stresses on the transformer coils depend on the square

of the current, so that if the short-circuit current is twenty times the full-load current the stresses become $20^2 = 400$ times the normal stresses; this means that the windings must be specially braced to resist mechanical stresses resulting from short-circuits. From this viewpoint the *delta-star* or "*A*"*-star* connection is favoured because a single-phase short-circuit on the secondary (*star* side) of a *delta-star* or "*A*"*-star* step-up bank of transformers causes a smaller short-circuit stress than on a *delta-delta* connected bank of transformers. It is the line side, and especially the e.h.t. line side, where short-circuits arise from flashovers and faulty insulators, and fully 90 per cent. of short-circuits are of the single-phase class.

Dangerous internal surge voltage troubles are in no small way due to arcing earths on isolated neutral systems. For those surges resulting from faults to earth, in which the return path is earth, the surge impedance depends upon the height of the line-conductors above the ground line and the position of the neutral plane with respect to the earth's surface. The approximate average variation of the reactance to earth, assuming the reactance of one conductor to neutral as 100 per cent., is somewhat over 200 per cent. of the reactance of one conductor with earth return. In view of the fact that the resistance of the earth path can be much less than the resistance of the conductor circuit (taking lines in general) there is every reason to believe that the best use should be made of this natural gift (the earth) for the protection of systems and for protection of life and property from dangerous impressed or induced internal and external voltages.

When transmitting electrical energy by cable (underground insulated cable), the line impedance is usually small, and therefore very large short-circuit currents are liable to flow if special precautionary measures are not taken. Overhead open lines, on the other hand, have a much higher impedance, and in consequence there is a larger voltage drop for the same length of circuit. For the same conductor section the resistance is the same, but the losses in conductors are of less consequence than the reliability of transformers and plant connected thereto, and should never be regarded as the sole deciding factor. For a given conductor metal and system, the voltage drop can be theoretically increased by either diminishing the sectional area of the conductor or by increasing its length—the transformer can be made to do the same in a much better way. However, with respect to the overhead line, it has inherent protective advantages over the underground cable because of the higher reactance. For either system, the maximum voltage drop would be limited by Regulations, assuming normal

service conditions. The greater inherent reactance of the shorter overhead line gives it the desired advantage at times when most

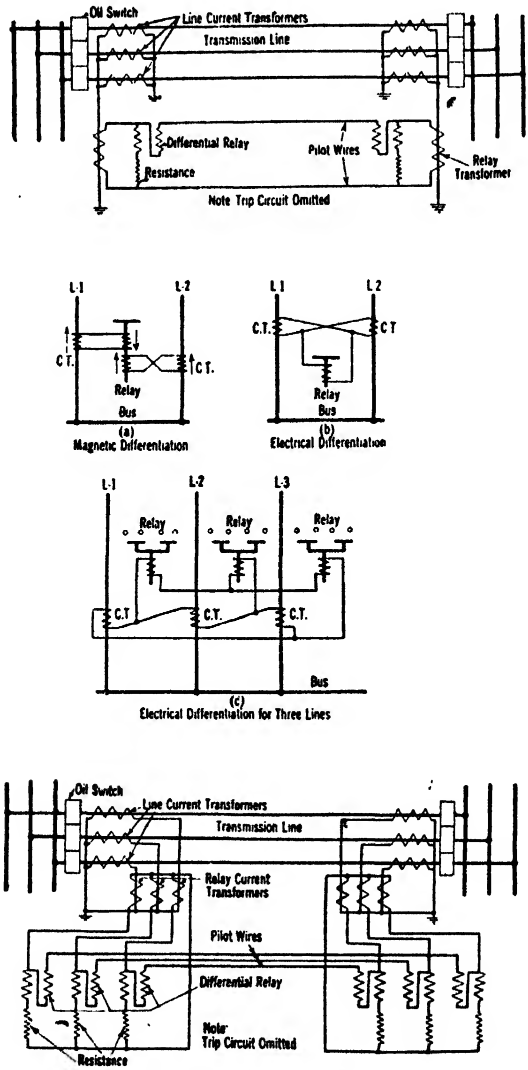


FIG. 28.—Methods of Protecting Transformer Systems.

required, *i.e.* during short-circuit conditions. For normal service there is a comparatively small increase in voltage drop, but the damping effect on short-circuit is very pronounced. The control of the short-circuit load is largely a question of suppressing the short-circuit current. The overhead distribution network usually

has the advantage in that the line voltage may be more readily increased, the number of transformers subdivided, or the impedance increased just when and where considered most necessary.

With respect to increasing the system voltage for any purpose, the practical scope of the present-day Regulation ($\frac{3}{16}$-inch ice and $\frac{3}{8}$-inch ice) loading, *based on voltage*, is made clearer. As 3300 volts will kill as surely as 11,000 volts, and as the line for the latter voltage is usually somewhat more robust, or at least as strong but lighter in weight for equal power transmitted, or for equal weight of conductor permits of the transmission of a much greater load and allows of much greater and wider extensions and electrical development, etc., it is hardly logical to choose the 3300-volt construction when the 11,000-volt system costs relatively little more for a greater kVA delivered, and enjoys a wider scope of usefulness. Even if the Regulations for line construction were such that the lighter Regulation loading included lines of 6600 volts (bearing in mind that in no respect can voltage affect climatic loading) it would not be permissible under the Regulations to put in transformers with primary windings arranged for 11,000/1·732 or 5500/11,000 volts and operate the system for 11,000 volts when the load has increased to warrant such a change. The point raised here is this, that quite apart from the Regulations impeding extension and electrical development, double winding and other transformer winding arrangements cannot be employed to the best advantage while such restrictions exist.

In the case of a short-circuit to earth, or an overload, the *star-delta* connection of transformers with solidly earthed neutral attempts to maintain an equal voltage on all phases. For instance, should an earth occur on the line, the transformers will supply current to the earthed line-conductor irrespective of its location. Also, should a rural group of small transformers be connected to a large distributing centre or station, and have its neutral solidly earthed, it will be subjected to a relatively worse type of short-circuit when an earth occurs on the line, and the higher the system voltage, the longer the line, and the smaller the transformer units, the more serious will be the effect of the short-circuit. In view of this, there is relatively greater risk in installing small installations with solidly earthed neutral because of the strain which frequent short-circuits impose on them; on the other hand, of course, there should be no such thing as frequent short-circuits.

The simplest system to protect is a radial system, *i.e.* a system where the feeders radiate from a distributing centre; but the scheme of system protection depends on the type of distribution,

varying with the voltage and length of system, also on whether the system is radial, of the parallel-feeder arrangement, employs the simple ring or loop or the ring system with parallel feeders. Several systems of protection are in general use; this country specially favours the pilot-wire schemes, which reduce the maximum time factor below that of time-delay relay schemes. Whatever scheme is used, it should seek to guard the stations and transformers and obviate heavy disturbance or system shut-down.

The main problem is to guard the system against a shut-down, and to this end the "discriminating" features in protective relay designs and schemes of connections have been made so perfect that a faulty section is disconnected upon the occurrence of trouble, and this is accomplished so quickly that little disturbance is noticeable on the remainder of the system and no service is interrupted.

As the size of the system increases, troubles may multiply, and the system may require greater thought in layout and more careful maintenance to give a service to meet with modern requirements. The increase in size and complexity of systems, with the necessity for uninterrupted service, have brought about the demand for more efficient and complete relay protection of the interconnected and larger transmission and distribution networks. Modern practice in the transmission of electrical energy has been towards larger and more complicated networks of interconnected lines and stations, rather than a greater number of relatively smaller isolated systems. For this country, the 132,000-volt National "grid" system of interconnected main lines and stations is (unfortunately, from many aspects) under bureaucratic control, and will, in consequence, be partly subjected to the usual secrecy of government departments as regards information. Up-to-date methods of protection against short-circuits and other faults offer all the advanced refinements and the new designs, schemes, and connections of modern practice. To-day, the protective relay has been so highly developed that it can be depended upon to protect against almost any defect or abnormal condition that can occur on a system. Of the various kinds of relays in use, they (respectively) detect or protect the circuit or apparatus or plant against overload, overvoltage, excess current, undervoltage, reverse current or reverse power, high- and low-frequency, high and low temperature, reverse phases, excess mechanical stress, gaseous pressures, etc.

Simple radial schemes can be protected from faulty line conditions by means of over-current relays. A ring or loop system, that gives each substation on the loop two circuits over which it can draw energy, makes possible continuity of service; the

simple radial system cannot guarantee continuity of service. For the loop system, directional over-current relays are installed at the generating end and on each side of each substation, so that when external trouble occurs on any section between stations, the relays at each end of that particular section will disconnect the faulty circuit from the transformers without disconnecting other services. At the substations, directional overload relays are installed so that they will operate to close the tripping circuit only when the excess current flow is away from the substation; the relays on the same side of successive substations are set so that the relays between the fault and the nearest substation will always trip first, thus ensuring that only the faulty section will be disconnected. In this respect one of the most effective protective devices is the impedance relay, the efficiency of which depends upon the nearness to the fault or short-circuit. Therefore, no time setting is required, as the relays nearest on each side of a ring-system fault will operate before any of the other relays on the system; this type of relay can be used at all stations on the system. For relatively short sections of a transmission system pilot-wire schemes are in common use, and have long been in special favour; this method of protection has the advantage of quick disconnection, selective action, and freedom from time setting.

In this country it has been common practice to employ the core balancing, the circulating current, the self-balancing and other protective systems and schemes of connections.

Station power transformers are usually protected by one of the differential methods. In these methods the current transformer ratios are chosen so that the secondary currents are equal; hence, load conditions will affect both equally, so that normally no current will enter the relay. When trouble develops in the transformer windings, the unbalanced current will operate the relay and disconnect the power transformer from the circuit. If relays are connected on the supply side of transformers supplying industrial loads (say at a factory), they not only protect the transformers but the motors as well, opening the circuit in case of trouble in the transformers. For industrial transformer installations it is often a question of—shall we install one polyphase unit or one bank of single-phase units, or shall we split up the total kVA capacity into two polyphase units or two banks of single-phase units? In general, but depending on the size and importance of the installation, one big unit is not so desirable as two smaller units, or one bank so flexible as two, of the same total kVA output.

On the high-tension side of station transformers, the bushing insulators sometimes flash over to the tank. To give protection against this class of fault, relay current transformers are installed inside the power transformer; in this way the required protection is afforded as well as protection against earthed windings due to other causes. Another use of the differential current relay is for faults between turns or windings. This class of fault will cause heavy fault current to flow in the short-circuited turns, but this current may not appear in the transformer leads of the faulty winding, and the unbalance current may be too low to operate ordinary differential current relays. A restrained percentage current differential relay should take care of this class of fault.

Plain overload protection is generally installed on small single units or banks of transformers. It is a simple matter to install a relay which will instantly locate internal trouble in a transformer unit or bank and cut out a defective unit without interruption of the load. However, in the case of parallel operation, when a short-circuit occurs the sound transformers may feed the defective transformer from the secondary side and cause an actual reversal of power in the defective unit, so that power feeds into the transformer from both sides. In such a case the sound transformers as well as the defective transformer will become heavily overloaded. Overload protection will disconnect the transformers, and the differential method of protection will disconnect only the defective unit and throw the load on the remaining units.

The installation of a differential relay will cut out of circuit the faulty transformer, but, by doing so, throw the full load on the remaining units; if the remaining units are too small, or the load too great to be safely carried by them, overload relays must necessarily cut out the sound transformers to prevent further damage. Under normal operating conditions, load conditions will affect the secondary currents equally, hence no current will enter the differential relay. It is the function of this relay instantly to locate trouble in a transformer and cut out the defective unit without interruption of the load.

The functioning of practically all protective devices depends either on the current, on time adjustment, or on certain electrical changes or conditions. What is desired is some device that indicates a fault in its initial stage without disconnecting the transformer if no immediate danger is present. The correction of minor faults, thus indicated, can be undertaken at the time of lowest load, when the transformer can be cut out, thus avoiding a costly shut-down or an expensive fault occurring at a future date. With such a

device the danger of transformer burn-outs is reduced to a minimum, as are also interruptions of service. A scheme of transformer protection is now in use that gives a broader scope of usefulness than the differential relay, because it also indicates or gives an alarm for low oil-level or oil leakage, entrance of air, faulty gasket or stopped circulating pump. The working of the scheme depends on the magnitude or relative danger of the internal fault; in the case of a "hot spot" or local heating of the windings, usually accompanied by more or less rapid accumulation of gases or vapour (depending on the type of fault), these are trapped and either work an alarm or trip the circuit-breakers.

Transformer turn-to-turn internal failures may cause damage very quickly if some kind of quick-acting protection is not provided. A method of protection depending for its working on the temperature of the oil or temperature measurements of the winding may be practically useless; temperature-indicating or measuring devices or alarms are sometimes installed between windings to locate quickly "hot spots," but they may be installed at points on the windings where turn-to-turn faults do not develop; the remedy is to install a type of differential relay acting on low current for this particular fault, and working through a separate relay winding.

The type of differential relay or other protection will depend on whether the neutral of the system is earthed or not, because the method of earthing the system has an important bearing on the protective scheme to be adopted. When the neutral is solidly ("dead") earthed, or earthed by means of a very low resistance, the protective scheme designed to operate on short-circuit usually also protects against earths. With the neutral system earthed through effective resistance, supplementary earth protection is required. For isolated neutral systems protection is obtainable by more complicated methods, depending on the system voltage and magnitude.

The differential earth relay method is in successful use on e.h.t. transmission systems where there are no parallel balanced lines and where the transformers are operating with earthed neutrals. This type of relay can be operated by two current elements or by one current and one potential element; one of the current elements is supplied from the neutral or residual bushing of the current transformer in the line to be protected, and the other element supplied from a current transformer in the neutral earth lead of the earthed power transformer. The relays may have the elements combined in one disc of the relay, or they may have separate

over-current and directional elements with the directional disc operated by two currents and the overload disc operated by one current. It is found that the one disc is in general the more reliable.

The study of earth current protection should be independent of overload protection because the power load current is usually heavier than the earth current; reverse power relays can operate for one condition, but rarely for both. The method and effectiveness of the protection against earth fault current also depends on whether we are using the resistance-earth system or the solidly-earthed system; for the latter system, an instantaneous form of protection is generally necessary to clear a fault in the shortest time.

Earth protection of transmission systems can be effected by the usual relays on a solidly-earthed system. If the system is operating with isolated neutral, or is earthed through a limiting resistance, it is necessary to provide additional protection to take care of line earths. This is ordinarily done by inserting a relay in the neutral connection of the line relays, which is operated by the unbalanced current that flows in the neutral when the line becomes earthed. If an earth occurs on a relatively low voltage isolated neutral (insulated) system, devoid of capacity current, the disturbance may not involve a short-circuit, but the "kick" is often sufficient to cause instability or operate the circuit-breakers.

As a protection against a phase-conductor falling on the ground, the transformer neutral can be earthed through a current transformer, the secondary of which is connected either to a relay, alarm, or other device, depending on the system, its voltage, its location, local conditions, and requirements. If a relay is used, it can be adjusted to operate when less than one ampère of current flows through the earth connection. It should not operate for current flow in the neutral due to unbalanced load, but it should operate for any current returning to the transformer from a phase-conductor falling on the ground.

The installation of choking coils and excess voltage arresters, both of which are specially adaptable for the protection of inductive apparatus such as the transformer, usually go together; the former is placed where most favourable to the transformer, while the latter is installed where most favourable to the line. That is to say, no bends or curves in the conductor should exist between the choke coil and the transformer, and the same conditions should exist for arrester and line; but decidedly sharp bends are usual between the arrester and the choke coil.

The path into an arrester should be as free as possible from turns, especially from sharp turns; this rule applies equally as much to the earth connection, which should be independent of that of the transformer. At stations it is common practice to install a general earthing-bus, *i.e.* one general earth consisting of one or more buses for the transformers, arresters, neutral return, etc. For distribution transformers, the earthing connection of arresters or of the transformer neutral and case is best made and is most effective and permanent for the line construction mentioned in Chapter X. This also applies to the "*lightning*" conductor (commonly called overhead ground wire) which, by its insulation and by means of an air-gap at certain poles or supports, can be given an air discharge path and used as a neutral return conductor or as a spare phase-conductor. This "lightning" conductor has *four* distinct functions, namely: continuous lightning conductor or overhead earth wire, neutral return conductor, spare power conductor, continuous overhead guard wire.

There are two classes of excess voltages, one external and one internal. Both kinds can be rendered harmless by dissipating the energy contained in them through damping or energy-consuming equipment, such as one or more types of arresters, choking coils, discharge fuses, cut-outs, earth coils, overhead earth wires, damping resistances, etc. One of the principal problems of design and construction is to prevent the initial excess voltage. To this end the overhead earth wire, running along the tops of the poles or structures, is used to reduce the induced charges and thus minimise outages, duty on arresters, etc. Not unlike the arrester, the overhead earth (ground) wire is installed to safeguard valuable apparatus against damage by over-voltages; the system or circuit neutral point is earthed for the same purpose. The isolated neutral system must, therefore, run a greater risk than the earthed neutral system; in other words, for the former system, the pressure is higher for the same degree of protection. From the protective standpoint, the earthed system will inherently possess advantages over the unearthed system or circuit. Arcing earth voltages, which usually pile up to several times normal value between line and earth, do not appear on earthed systems unless the system is of considerable extent and the path from line to earth is of high impedance, which condition is quite possible where the practice is to earth at the supply end *only*. Also, earthed systems allow the use of lightning arresters of reduced rating in many instances, thereby permitting an improvement in protection.

It cannot be overlooked that, as the entire kVA capacity of a

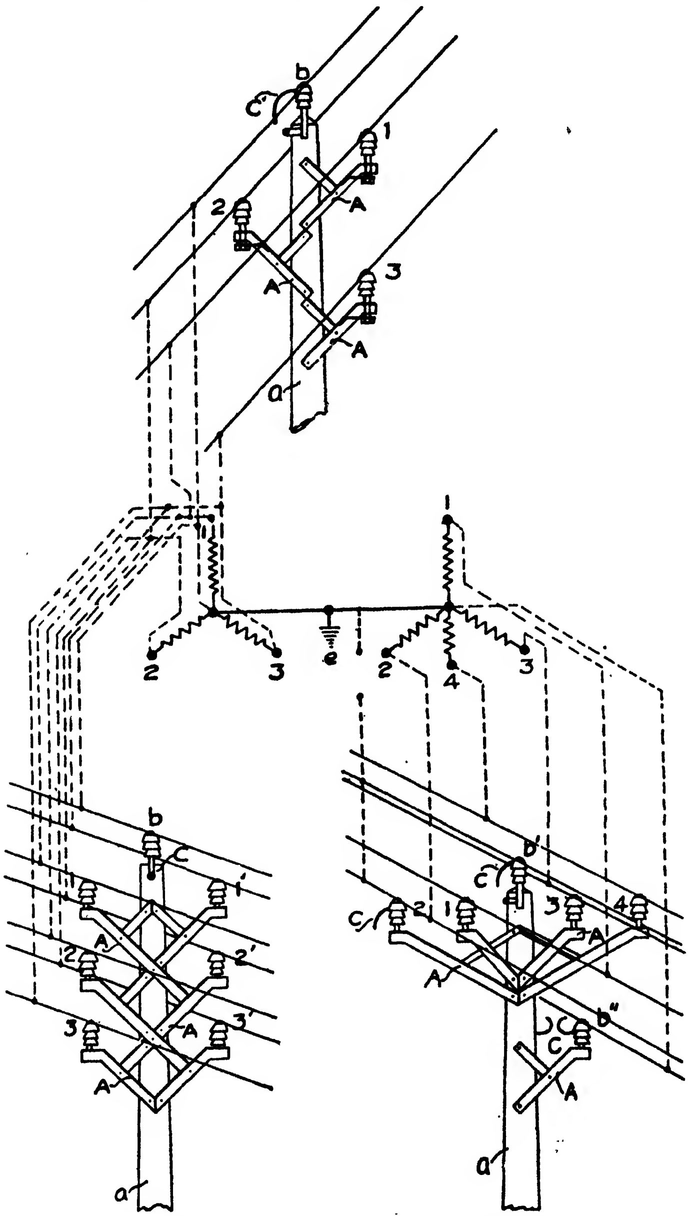
main transmission or distribution network increases, due to more generating stations and main lines being interconnected, so the energy flowing into a short-circuit and the magnitude of disturbance will also increase. To deal with defects occurring on such a network, larger capacity circuit-breakers will usually be required. In other words, the short-circuit current can be reduced by increasing the reactance of the network at determined points and dividing up the network, *i.e.* operating each large substation from a fewer number of generating stations. The reactance of the transformers may be increased so that the impedance voltage is high (12 or 14 per cent.). The normal reactance of 50-cycle power transformers of the larger station type ranges between 8 and 12 per cent.; for intermediate substation units, the normal reactance values usually range between 3·5 and 6 per cent.

The power transformers at each substation of the 132,000-volt National "grid" are *star*-connected on the high-tension side, with the neutral solidly earthed, and *delta*-connected on the secondary side with a true earthed neutral provided by means of a "*Z*"-connected tertiary winding, which latter is to be employed to provide power for small auxiliaries in the station. Each transformer is protected on both sides by overload and balanced leakage relays.

As regards graded time delay relays, they would appear to be fundamentally unsound in principle for stability purposes and for limiting danger due to heat generation on solidly-earthed systems having large capacity current to earth, such as the National "grid" main transmission system. For such systems, practically instantaneous elimination of faults is desirable, and, where many stations are involved, time delay cumulation may be a serious disadvantage and may involve a limit on future requirements, viewed from the protective standpoint.

Earthing at the substation and/or at the primary feeding-points of the distribution network provides for better protection against lightning than non-earthing; also, some protection from lightning is secured by installing spark-gaps on the neutral at each distribution transformer installation. Where it is known that transformers have been burned out by lightning, a spark-gap protection should be installed on the secondary side where mains are strung on the same poles as the primaries, which latter are always better insulated and require, from this viewpoint, less protection from lightning than secondary mains for the same height of conductors above ground line. Practice indicates that, in order to protect all parts of the secondary system against excessive voltages to earth and to protect single-phase lighting transformers against

FIG. 29.—Steel, Wood, or Concrete Construction. Showing Methods for Protective Line Construction against Arcing Earths, Induced Voltages, Flashovers, etc.[1]



The pole-*insulated* earthed wire (b) or guard-wire (b'') is used as mentioned in fig. 30. The arms may be of steel; they mitigate bird troubles, they combine the steel brace and arm attachments into one unit, and they are of a form to facilitate any arrangement of conductors.

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[1] Patents granted.

excessive voltages, the neutral conductor of the distribution system should be earthed not only at the station but at a sufficient number of points along the exposed mains, *i.e.* at service connections (see Chapter VIII).

For the protection of transformers against high-frequency impulses it is usual to insert choke coils in series with the line on each transformer outgoing lead. As the type more commonly used fails to smooth out the steep front of the wave before it reaches the transformer winding, it has been found desirable to reinforce the transformer insulation between turns for about 5 per cent. of the end winding; in countries subjected to severe atmospheric conditions, a larger part of the high-tension winding is reinforced. For the higher-voltage systems, air type choke coils are designed so that during normal operation the impedance of the coil to the flow of current is practically only that of the ohmic resistance; hence, the benefits derived from the use of the choke coil at times of lightning storms far outweigh the very slight drop and loss under normal conditions, which can almost be taken as nil. This is the reason why choke coils are universally employed on e.h.t. systems for choking back steep wave-front high-frequency voltages. Of recent years a choke coil has been in use with ohmic resistance connected in parallel; this is supposed to suppress the wave energy and flatten out steep-fronted waves. Various choke-coil types of surge absorbers are in use that dissipate the energy in the surge without the necessity of earthing the system.

The ordinary distribution transformer for overhead lines is usually protected by means of fuses, which may be of the expulsion type or the ordinary fuse wire connected across horn breaks. The protection given to the industrial type of transformer is usually that of overload protection; if greater protection is desired, one of the leakage methods or the time-limit fuse or some form of relay protection can be used. When transformers are operated in parallel, ordinary overload protection is not sufficient.

For overhead or vault type of distribution transformers the universal practice for their protection is to use fuses. Such a practice may result in damage to the transformer by overload where a single fuse of a bank is blown. Where the neutral is earthed, two of the three phase-windings will carry all the load when one fuse blows, and carry this load at a much lower power factor than normal. If no means are provided to indicate a blown fuse, the remaining transformers may burn out. One satisfactory way to overcome this is to install a relay in the neutral; this also provides for some form of alarm when a fuse blows.

For distribution or service transformers we may fuse the primary to protect against ordinary overloads, or we may fuse for short-circuits only. The primary object in both cases is to protect the main service by isolating the defective part of the circuit. One of these two methods will permit of service outages before the transformer is in danger, while the other method will permit the transformer to fail when continuously overloaded.

The different kinds of fuses in use for the protection of transformers are the ordinary link type, the enclosed type, the oil type, chemical type, explosion type, horn gap type, capsule type and throttle type. For rural distribution transformer installations of from 10 to 100 kVA, the expulsion type of fuse is more generally used.

Fusing for double or even triple full-load current can reduce service interruptions to a minimum (each installation or case should be judged separately). Sometimes double fuse rating is desired because a lower capacity fuse blows when the transformer is switched in; when switching-in certain transformers there is sometimes a heavy current rush in the primary, sufficient to blow fuses rated at more than 75 per cent. greater overload than normal. Because of this, and for other reasons, it is sometimes the practice to rate the primary fuses of distribution transformers not for the protection of the transformer itself from overloads, but for the purpose of disconnecting a defective transformer so as to protect the remainder of the service. In other cases it is the practice to protect the transformer against overload (about 200 per cent.) by means of primary fusing. As fully 90 per cent. of the minor troubles occur on consumers' premises, it is safe practice to over-fuse the primary and rely largely on the secondary fuses on consumers' premises to blow (local circumstances will decide the safest practice to follow).

Fuses also afford protection against earth faults. The neutral conductor should never be fused; it should be permanently earthed at all times to afford protection. A fuse in a circuit will automatically open the circuit when excess current is drawn through it, and it will thereby protect the circuit against overheating with possible danger of fire. Fuses will also protect against short-circuits and overloads. In view of the reliable protective value of fuses for small installations, such as dwelling-house installations and transformers for lighting, there is every reason for relying on individual installations and over-fusing the primary side of distribution transformers as already mentioned.

The metal used for fuses usually consists of some form of tin

alloy or pure copper. Aluminium is also in use because of its low melting-point and high conductivity as compared with tin, lead, and certain metals; its disadvantages are crystallisation and oxidation. See Tables VIII and IX for tin alloy and copper.

TABLE VIII.

SIZES OF COPPER FUSES.

Diameter of Wire. (Inch.)	Equivalent S.W.G. Size.	Fusing Current. (Fusing Time =1 Minute.) (Ampères.)	Maximum Safe Working Current. (Ampères.)
0·0092	34	8·6	4·3
0·010	33	9·8	4·9
0·0108	32	11·0	5·5
0·0120	..	12·8	6·4
0·0124	30	13·5	6·8
0·0148	28	17	8·6
0·018	26	22	11
0·022	24	30	15
0·028	22	41	21
0·029	..	43	22
0·036	20	62	31
0·040	19	73	37
0·044	..	86	43
0·048	18	98	49
0·052	..	111	56
0·056	17	125	63
0·064	16	156	78
0·072	15	191	96
0·080	14	229	115

TABLE IX.

SIZES OF LEAD-TIN ALLOY FUSES.

Diameter of Wire. (Inch.)	Equivalent S.W.G. Size.	Fusing Current. (Fusing Time =2 Minutes.) (Ampères.)	Maximum Safe Working Current. (Ampères.)
0·020	25	3	2·0
0·022	24	3·5	2·3
0·024	23	4	2·6
0·028	22	5	3·3
0·032	21	6	4·1
0·036	20	7	4·8
0·048	18	10	7·0
0·064	16	16	11·0

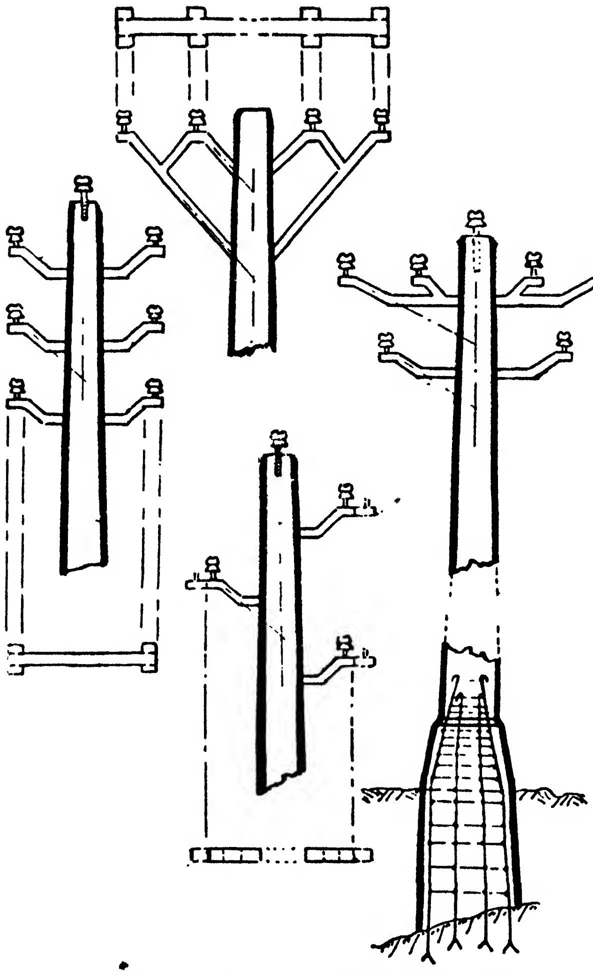

FIG. 30.—Reinforced-concrete Construction.[1]

This differs widely from steel construction; the whole of the exterior is semi-non-conducting and in consequence is not attractive to lightning. However, the arms and/or pins for the insulators are metallically bonded to the interior steel and are in good contact with earth. The arms are specially strong and of a shape to eliminate *bird* troubles, permit a plurality of insulators *per conductor* from one arm, the highest possible elevation of conductor for minimum height of arm attachment, outlets on any part of the pole for bonding or earthing any fixture, transformer case, switch, etc., the most effective discharge path from the overhead ground wire or/and neutral return conductor across an air-gap to the outlet contact and direct to an excellent earth without wires, thus providing protection from over-voltages on the combined overhead ground wire neutral return conductor (insulated from the pole or support), which is earthed at the most desirable points favourable to disconnection when it is required to use the overhead ground wire or/and neutral return overhead ground wire as a power conductor in an emergency (see also fig. 52).

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[1] Patented.

During the pioneer days of overhead line design and construction, engineers did not understand in the light of to-day's knowledge such matters as lightning voltage, insulator flashovers, arc voltage and its direct relation to arc length, and so forth; they were nevertheless well guided by circumstances and common sense in the erection of safe lines; they used wooden construction throughout, and kept the conductors low. After all these years of experience it is not as yet generally realised that where the resistance of steel structures or poles and/or the earth connections thereto is low, the total flashover voltage is much lower than with a wood pole or concrete pole line with or without low-resistance earth connection, and is still lower compared with a wood pole line properly installed and set in earth of high resistance, which latter is a natural consequence when the creosoted wood pole is used. Taking only one example of safety and reliability of a line, let us consider a primary distribution line designed for 11,000 volts, using pin type of insulators. The approximate impulse flashover for such an insulator is about 300 kV, and the average height of the bottom conductors for such a line is about 22 ft. This design, which is of the common type (without overhead ground wire installation), permits us to operate at no higher value than 14 kV per foot of height of conductors. This low figure is one of the reasons for recommending a change in designs to secure safer and more reliable lines. Another reason is that the line protection problem *should always include the transformers* connected thereto.

For protection against over-voltage we had in past years to rely almost exclusively on the lightning arrester; we reinforced the end-turn insulation on the transformers; later we installed an overhead ground wire; we then sought means to increase the flashover value of insulators, and the latest important practices put forward propose to keep the conductors low, either by means of conductor arrangement, restricting the sag or span, or by both of these means, to use wooden supports and insulate all wires and conductors from them, and to combine the neutral conductor and overhead ground wire, properly installed. The height of conductors and wires and their arrangement on the supports in relation to other conductors and wires (with or without transpositions of the power conductors), as also the kind of material used for supports (steel, reinforced concrete, wood, etc.), have much to do with increasing or decreasing dangers and hazards. The so-called "economical span theory" does not consider any of these problems, nor does it take account of the *real* safe height of conductors, the best stress on insulators, best insulation, best arrangement of con-

ductors in relation with the ground wire or wires, and many other factors.

Many advantages have accrued from the use of a properly installed neutral conductor as the overhead ground wire and/or continuous earth guard wire. No matter where it is situated on the line in relation to the power conductors, it offers desirable shielding value, positive relaying, better operating conditions, much decreased length of arc resulting from flashover, and longer time duration for clearance and quenching of an arc; all these aid the switch problem, etc. Excellent results are obtained when it is used on wood pole and reinforced concrete pole lines and insulated therefrom, especially for those lines operating at voltages of 33,000 volts and under, due to the induced potential gradients of the lower voltage lines being relatively more severe—see the accompanying summary of calculations (fig. 32). The long-standing practice of this country has been to locate the overhead ground wire (commonly called "guard wire") below the power conductors. It is, however, becoming more generally understood that raising the ground wire to the same level, or to a limited distance above the power conductors, is equal to lowering the height of the conductors above ground level so far as protection from induced potentials is concerned. In other words, we may say that placing the ground wire below the conductors is equivalent to raising the height of the conductors above ground level, *i.e.* if the same ground wire protection were placed above (or on a level with) the power conductors, for the same induced potential on the conductors this would be equivalent to placing them at a lower height above ground level, which would make for a safer and more reliable line. This advantage is further improved upon by retaining the insulation of all the supports, which results in increased flashover value, *i.e.* the total voltage is much higher for wood and concrete than for steel supports (structures, poles, pins, etc.). The three most dangerous conditions which transformers and overhead lines meet with come from direct strokes of lightning, induced potentials from thunder-clouds, and excess voltage steep-fronted waves resulting from flashovers. Good practice requires that a guard should be set up against the latter two dangerous external pressure rises. This is best accomplished by keeping the insulated conductors as low as is practicable, by properly installing the ground wire or wires, making and maintaining the line insulation high, fitting arcing rings to the insulator strings, and using efficient lightning arresters.

Because of the liability of building up of dangerous over-voltages, such line problems as the following should receive careful study:

(1) Shall we design a whole line for one condition of (rare, occasional, or frequent) maximum potential gradients?

(2) Is it necessary to build so that the whole line up to the transformers is immune from impulse charges?

(3) Shall an overhead ground wire (or wires) be used, and, if so, what will be the most economical effective number and arrangement in relation to the power conductors?

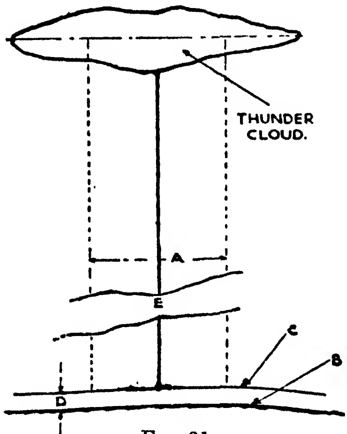


FIG. 31.

A = zone of great intensity.
B = ground line.
C = transmission line (insulated).
D = height of conductor above ground, in feet.
E = distance between cloud and line.
 = potential gradient in terms of height of power conductors above ground line, for practical purposes stated in terms of kilovolts per foot of height of conductors above ground.
c_1 = impulse or lightning flashover value in kV.

Thus, the maximum potential gradient on C is given as

$$f = 100De_1 \text{ kV}.$$

Where e_1 = protective ratio = voltage with ground wire/voltage without ground wire. Insulator flashover will not occur when c_1 *equals* f; c_1 is based on a steep-fronted wave. *The problem is that of determining the gradient exceeding* E *and the best practical means of increasing the impulse flashover* c_1, *decreasing the maximum induced potential or/and the protective ratio, or/and increasing the* kV *gradient per foot of height.*

In practice, insulator flashovers are a hazard to good service; a wave of steep front endangers the insulation of power transformers, etc.

(4) Will the addition of insulator units and/or grading rings be equally or more effective and equally or more economical than an additional ground wire?

(5) What is the safe maximum height of power conductors above ground line, and shall we design for it?

(6) To avoid flashovers of insulators, is it safer for the system (taken as a whole) to be over-insulated or shall we install another ground wire over the more frequently disturbed parts of the line, or decrease the height of the power conductors above ground level, or do both?

The induced potentials from lightning will break down the insulation of power transformers if not relieved by flashover from line insulators or/and switch bushings or/and transformer bushings or/and the lightning arresters themselves. Travelling waves of steep front should be reduced before reaching the station apparatus, and the simplest method is to have the height of conductors above ground level as low as is allowable and practicable; the second best method is to install ground wires at the most effective positions on the tower in relation to the conductors, as these tend greatly to reduce the induced potential on the power conductors; the earthed neutral should form part of the transmission system, so as to obviate oscillation and voltage rise.

The engineer knows approximately the average height of the conductors above ground level for the different dispositions and line voltages; this varies a little with span length, but can be very closely approximated for practical calculations. Depending on the arrangement and the line voltage, the vertical separation of conductors will vary somewhat; allowances have been made for this in arriving at the final figures given in the following table and summary:—

TABLE X.

Line Voltage.	Line to Neutral Voltage.	Maximum Line to Neutral Voltage.	Dry Flashover Voltage. (Effective.)	Dry Flashover Voltage. (Maximum.)	Number of Units.	Impulse Flash-over Voltage.	Factor of Safety.
132 kV	76·2 kV	108 kV	500 kV	700 kV	9	1300 kV	6·4
110 „	63·5 „	90 „	400 „	565 „	7	1150 „	6·4
88 „	50·9 „	72 „	360 „	500 „	6	900 „	6·9
66 „	38·2 „	54 „	310 „	430 „	5	760 „	7·9
44 „	25·4 „	36 „	270 „	360 „	4	620 „	10·0
33 „	19·1 „	27 „	225 „	300 „	3	480 „	11·0
22 „	12·7 „	18 „	160 „	230 „	pin	340 „	12·7
11 „	6·3 „	9 „	85 „	120 „	pin	300 „	13·3

The safety of any line depends on the maximum induced voltage for the potential gradients afforded by the particular design and construction. For the worst conditions, the relations between the maximum induced voltage and the lightning flash-over value for insulators are approximated in Table XII.

Up to the present time, and conforming to the general practice of this country, we have very largely limited ourselves to the low values (c') given in Table XI.

TABLE XI.

Maximum Line to Neutral Voltage.	Line Voltage.	Impulse (Lightning) Flashover Voltage.	kV per foot of Height for: Line Voltage.		kV per foot of Height for: Impulse Flashover Voltage.
(a')	(b')	(c')	(a')	(b')	(c')
108 kV	132 kV	1300 kV	2·3	2·8	27·6
90 „	110 „	1150 „	2·0	2·6	25·5
72 „	88 „	900 „	1·8	2·2	22·5
54 „	66 „	760 „	1·5	1·8	21·7
36 „	44 „	620 „	1·2	1·4	20·6
27 „	33 „	480 „	1·0	1·2	17·4
18 „	22 „	340 „	0·75	0·9	14·1
9 „	11 „	300 „	0·41	0·5	13·6

In terms of three different potential gradients, taking 50 kV per foot of height as a mean figure for reference, the maximum induced potentials for lines without ground wires and in terms of the bottom conductors only, are given in Table XII. It will be seen that the voltages are far too high, and it is evident that other practices must be resorted to, such as the use of insulators of higher flashover values, the installation of overhead ground wire or wires, or/and the insulation of all wires from them, etc. Much information can be obtained from the accompanying tables; for instance, one of the common beliefs is that lines under 11 kV obtain relatively no protection as compared with lines of the order of 110 kV—the approximate relations are given in Table XII, but the more correct relations are forcefully brought out in the final summary of fig. 32.

TABLE XII.

Line Voltage.	Number of Units.	Average Height of Bottom Conductor.	Impulse (Lightning) Flashover Voltage.	Maximum Induced Potential (*without Ground Wires*) *for Potential Gradients of:*		
				(25)	(50)	(75)
132 kV	9	47 ft.	1300 kV	1170 kV	2350 kV	3520 kV
110 „	7	45 „	1150 „	1120 „	2250 „	3370 „
88 „	6	40 „	900 „	1000 „	2000 „	3000 „
66 „	5	35 „	760 „	870 „	1750 „	2620 „
44 „	4	30 „	620 „	750 „	1500 „	2250 „
33 „	3	27 „	480 „	670 „	1350 „	2020 „
22 „	pin-type	24 „	340 „	600 „	1200 „	1800 „
11 „	pin-type	22 „	300 „	550 „	1100 „	1650 „

Transposing the power conductors complicates the results, due to changing the conductors to different levels and to different distances from the ground wires; the differences, however, will not materially alter the design relations shown here and desired in practice. It will be seen that, for the same disposition of conductors and method of protection, the induced potential gradients differ for the different voltages. This is due to the fact that the vertical separation of conductors is not the same for the different line voltages—this is so, independent of the height of bottom conductors, which decreases down to a minimum limit as the voltage is decreased. The accompanying sketches are for line voltages up to 33,000 volts; above (or at) this voltage the suspension insulator can be used, but the vertical separation need not be changed. Table XIII is for voltages of from 6,600 up to 66,000 volts.

It is interesting to note from Table XIII that the relatively

least protected overhead line, for the different conductor dispositions and protective arrangements shown, is (*a*) of fig. 32. Improvements can be made by arranging two ground wires at the top, or as shown in (*c*), which latter offers a slight improvement over ground wires located at the top of the tower (one above each of the top conductors). Locating one lower ground wire as shown in (*c*) results in less mechanical stress as well as other advantages. It is interesting to see that, for the lower voltage lines, (*c*) type is the best of all the types, with (*d*) second best. For the horizontal arrangement of conductors, (*e*) runs very close to (*d*) for all line voltages, with the advantages in favour of (*d*); (*d*) offers good all-round protective merits, but (*e*) is best constructionally.

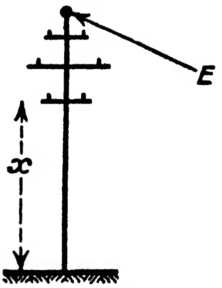
For equal line insulation and equal height of lowest conductors above ground line, and for an equal number of conductors and ground wires, the lines safest from induced potentials, taken in order of importance, are as in the following table:

TABLE XIII.

Line Conditions.	Approx. Maximum Potential Gradient at which Insulators will Flashover (in terms of kV/ft. of height) for:		
	66–44 kV Line.	33–22 kV Line.	11–6·6 kV Line.
a	80	68	50
b	60	50	32
c	54	46	29
	Transformer Designed Test-voltage in kV.		
d	100–190	60–100	23–40

(*a*)=Line with ***equilateral triangle*** arrangement of power conductors, with base of triangle flat; one ground wire located on each side of the lower conductors. For this arrangement the top conductors are most affected.
(*b*)=Line with ***horizontal*** arrangement of power conductors, with two ground wires located above the six conductors.
(*c*)=Line with ***vertical offset*** arrangement of power conductors; one ground wire above each of the two top conductors. For this arrangement the bottom conductors are most affected.
(*d*)=Relative transformer test-voltage.

It is thus seen that the line offering the best protection from excess voltage is the *equilateral triangle* arrangement of conductors; the operating electrical merits of this arrangement are already well known to engineers. The writer therefore recommends this arrangement for transmission lines in particular and primary distribution in general, and the arrangement of two ground wires

Three-phase double-circuit lines, showing different arrangement of conductors and number and positions of overhead ground wires.	Line voltage in kV. (E′).	Impulse flash-over of insulator in kV.	Maximum induced potential in kV for (a). (Middle conductors)	Maximum induced potential in kV for (b). (Bottom conductors)	Percentage voltage *above* impulse flashover value of line insulator, in kV for (a).	Percentage voltage *above* impulse flashover value of line insulator, in kV for (b).	Transformer test pressure in kV for: Approximately average conditions.	Transformer test pressure in kV for: (3·5E′ kV.)
 (a)	132	1300	3070	2980	136	119	270	460
	110	1150	2860	2790	149	142	230	380
	88	900	2500	2480	179	174	180	300
	66	760	2130	2170	180	185	140	230
	44	620	1770	1860	185	200	100	150
	33	480	1560	1680	204	250	80	115
	22	340	1360	1490	300	338	60	75
	11	300	1250	1370	316	354	30	45

E—Ground wires. *x*—Height above ground level of bottom conductor.

FIG. 32 (*a*).—Showing the approximate Relative Values of Transformer Test Pressures, Induced Line Potentials, and Impulse Flashovers of Line Insulators.

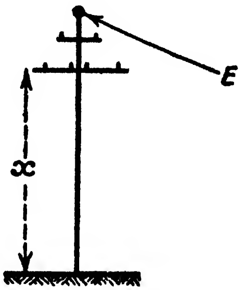
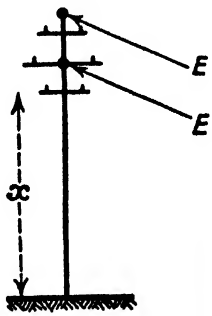
It is of interest to *compare the insulator flashover values with the insulation strength of transformer windings.*

located one on each side, also to serve as the neutral return conductors (lightly or ordinarily insulated at each support) and for relay protection, and, as desired, for guarding; also for use in case of a broken power conductor or similar mishap.[1]

Experience indicates that there is more reason to discuss troubles arising external to the transformer than those originating in the transformer. As 90 per cent. of all troubles originate external to the transformer, it is incumbent on operating engineers to pay special attention to the location, design, construction,

[1] Improvements in or relating to Electrical Transmission and/or Distribution Systems. Patent No. 311013.

maintenance and operation of lines, so that hazards are reduced to a minimum. Obviously, those lines subjected to the least troubles, or subjecting the system to the least shocks, are the safest and best from the transformer viewpoint. Hence, both

Three-phase double-circuit lines, showing different arrangement of conductors and number and positions of overhead ground wires.	Line voltage in kV. (E').	Impulse flashover of insulator in kV.	Maximum induced potential in kV for (a).	(b).	Percentage voltage *above* impulse flashover value of line insulator, in kV for (a).	(b).	Transformer test pressure in kV for: Approximately average conditions.	(3·5E' kV.)
			(Top conductors)	(Bottom conductors)				
	132	1300	2770	2500	113	92	270	460
	110	1150	2590	2380	125	107	230	380
	88	900	2260	2120	150	135	180	300
	66	760	1930	1650	154	117	140	230
	44	620	1600	1590	158	156	100	150
	33	480	1410	1430	193	200	80	115
	22	340	1220	1270	258	273	60	75
(b)	11	300	1130	1170	277	290	30	45
			(Top conductors)	(Middle conductors)				
	132	1300	2560	2240	97	72	270	460
	110	1150	2200	2010	91	74	230	380
	88	900	1940	1800	115	100	180	300
	66	760	1690	1660	122	118	140	230
	44	620	1370	1300	120	110	100	150
	33	480	1190	1140	157	137	80	115
	22	340	1080	1030	211	202	60	75
(c)	11	300	940	910	213	203	30	45

E—Ground wires. *x*—Height above ground level of bottom conductor.

FIG. 32 (*b*), (*c*).—Showing the approximate Relative Values of Transformer Test Pressures, Induced Line Potentials, and Impulse Flashovers of Line Insulators.

It is of interest to *compare the insulator flashover values with the insulation strength of transformer windings.*

lines and the transformers connected thereto should as a general rule be considered as one composite unit. The hazards involved come from excess voltages and currents, these being due to lightning, faults to earth and arcing earths, flashovers, short-circuits,

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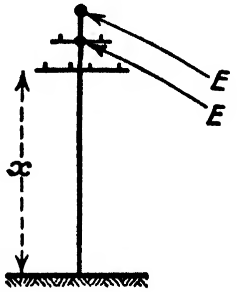
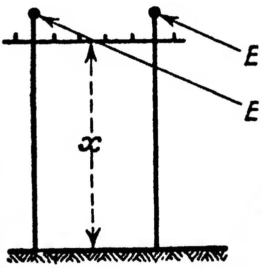
etc. The protective design and construction referred to in this book serve to place a check on, or mitigate, hazards reaching the transformers.

Three-phase double-circuit lines, showing different arrangement of conductors and number and positions of overhead ground wires.	Line voltage in kV. (E').	Impulse flashover of insulator in kV	Maximum induced potential in kV for (a).	(b).	Percentage voltage *above* impulse flashover value of line insulator, in kV for (a).	(b).	Transformer test pressure in kV for: Approximately average conditions.	(3·5E' kV.)
 (d)	132	1300	2130 (Top conductors)	1980 (Bottom conductors)	64	52	270	460
	110	1150	1980	1890	72	61	230	380
	88	900	1730	1680	92	86	180	300
	66	760	1480	1470	97	96	140	230
	44	620	1230	1260	98	103	100	150
	33	480	1080	1140	125	137	80	115
	22	340	910	1000	176	193	60	75
	11	300	870	930	190	210	30	45
 (e)	132	1300	2020		55		270	460
	110	1150	1940		68		230	380
	88	900	1720		91		180	300
	66	760	1500		98		140	230
	44	620	1290		108		100	150
	33	480	1160		141		80	115
	22	340	1030		202		60	75
	11	300	940		213		30	45

E—Ground wires. *x*—Height above ground level of bottom conductor.

FIG. 32 (*d*), (*e*).—Showing the approximate Relative Values of Transformer Test Pressures, Induced Line Potentials, and Impulse Flashovers of Line Insulators.

It is of interest to *compare the insulator flashover values with the insulation strength of transformer windings.*

CHAPTER VII.

OPERATING TROUBLES.

The greater part of the work connected with electrical operation is necessarily of a routine nature, but it requires men of wide practical experience in actual operating service, including inspection and dealing with troubles.

The growth of operating service requirements has made interruptions so costly that it is felt that the very best engineering talent is necessary to maintain the desired continuity of supply. The "troubles" section in particular offers the very best opportunities for active, wide-awake, thinking men. Operation and maintenance demand a man's best efforts, absolutely regardless of hours, sleep, pleasures, and so forth; but, in return for these sacrifices, invaluable experience is obtained that cannot be obtained in any other way or in any other branch of electrical engineering. An engineer may at every available moment read about the design of machinery and apparatus, and thus gain a certain amount of knowledge, but he cannot get experience by this means nor truly understand the limitations, etc. of systems and equipments. He may acquire the best knowledge of calculus and hyperbolic functions, but the ability to do things and direct work with safety, think quickly with a practical mind, obey orders implicitly, etc., are the main requirements, obtained only by sacrifice of pleasures, by hard service, and by long and continuous operating experience full of trials.

Incipient failures are discovered and breakdowns can be avoided by inspection; such are vital when electricity undertakings can least afford to shut down, *i.e.* during stormy weather, when usually carrying the peak loads. Inspection, therefore, increases the dependability of service because it results in fewer breakdowns. This applies especially to transformers. Transformer defects almost invariably lead to disturbances in the supply system, which cause losses in production, etc.

From an economic standpoint a decided economy results from periodic inspection of lines and underground distribution

transformers in particular. Inspection leads to the discovery of such defects as low oil-level, oil leaks, low dielectric strength of oil, presence of sludge, cracked, broken or leaky insulators, overload or/and unbalance of load, loose connections, dangerously heavy fuses, etc.

Good "troublemen" usually form the habit of continuously inspecting transformers in service. Their attention is particularly directed to blown or faulty fuses, broken or cracked bushings, signs of overheating, and those failures or troubles requiring more attention. They should report these findings to the section concerned. In cases of transformer overheating, load tests are made. The general routine followed by experienced "troublemen" serves to forestall troubles, because the vigilant watch kept reveals transformer installations that need attention before trouble actually occurs, and, in the case of failures, the cause of failure is revealed in such a way that steps are taken to prevent recurrence.

With the bigger undertakings it is sometimes the practice to subject all transformers received from the manufacturer to their particular tests. These tests usually are for ratio, core loss, heating, resistance, polarity, high voltage, etc. The tests are made as a check against the makers' guarantee, and also as an acceptance test. They also form a valuable record to the electricity undertaking, and are available for any future requirement in connection with location, parallel operation, rewinding, etc.

Each transformer, when received from the manufacturer, is given a history card that records every change observed from the time of its purchase until its final disposal. Apart from the record of troubles, rewinding, change of location, etc., the card shows the electricity supply company's serial number, makers' name and serial number, form, type, phases, frequency, high-tension and low-tension voltages, percentage taps, rated capacity, etc. The operating service record shows locations of installation, dates of removals, when placed in stock and when taken out of stock, when installed, class of troubles developed and their causes (such as burn-outs from overload, lightning, poor oil or low level of oil, etc.), when rewound, time and results of major inspections, dates of tests, etc.

The life of a transformer is usually the life of its insulation; when the insulation is destroyed or is faulty the transformer is not only useless but it may prove positively dangerous. As regards the insulation, the factor that has the greatest effect in reducing dielectric strength is moisture. This was well recognised in the pioneer days, and the transformer was then protected by having

its coils immersed in oil, so that no water could reach them; later on, protection was afforded by impregnating the fibrous insulation with a moisture-proof compound previous to its immersion in oil; these are also the practices at the present time.

It is sometimes found that transformers taken from stock, or held as standby in a station, substation, or switch-house, fail suddenly when put into service. Many such failures can be traced to moisture being retained in the iron laminations or on the end frames and other metal parts such as the tanks, to breathing, and to other causes tending to decrease the dielectric strength of the oil. When moisture is retained by the laminations it can be transmitted to the windings when they have become heated. With impregnated windings this trouble is not likely, the treatment not only giving mechanical rigidity but driving and sealing out all moisture, filling all interstices of the coil with an insulating substance, and solidifying the whole winding into a solid heat-conducting body. To avoid moisture condensation it is advisable always to operate transformers at several degrees above the surrounding air temperature.

The more common points for observation are: condition and location of high-tension and low-tension connections and wires; condition of transformer poles or structures and their supports; clearance of transformers from walls; condition of earth connections; condition of gaskets, bushings, outlets, disconnecting devices, choke coils; exposed terminal blocks; evidence of overheating and high temperature at time of inspection; level of oil and examination of leads for oil leak, syphoning of oil; abrasions; clearance between transformers and tank or case; unusual hum or sound; vibration; loose nuts, etc. The history card should always be examined for particulars of latest tests, unbalance of load, overloads, etc.

Not unlike the State Department that strives to prevent crime, a company that inspects continually and replaces at the right time does more than move in the right direction. To wait for a "repair attack" may amount to a kind of defence, but applying the *preventive* method is the safe and sure and more economical way of tackling the troubles.

A keen operator or "troubleman" has a sensitive ear to any change in the musical hum of the transformer which may indicate an unusual or abnormal operating condition. Lack of care respecting matters in general goes hand in hand with carelessness in operation. Imperfect operation is not merely a matter of overload, improper division of loads, poor condition of oil, presence of dirt,

moisture, and so forth; it often rests with lack of regular inspection and care of the distribution network, which brings trouble to the *transformer.*

Troubles of transformers in service may be classified under the following main headings:

(1) Those due to electrical breakdown in the coils, such as burn-outs from overload or other heavy current causes.

(2) Those due to external short-circuits, causing distortion to coils and other parts by electromagnetic action.

(3) Those due to breakdown of the insulation, caused by excessive voltage from lightning, switching, or other external disturbances.

(4) Those due to breakdown of the oil, caused by moisture or sludge.

The common type of station or substation transformer should preferably be given a bi-annual inspection of core and coils for signs of serious distortion, excessive black deposit (sludge) on windings and cooling coils, loose nuts, etc.

The evidences of carelessness for the most part show themselves in the various types of installations. The following should be looked for: leads burned inside the case or tank, due first to leakage, then arcing; mechanical strain or too much slack on leads to insulator bushings; syphoning of oil, which is a great danger; tools accidentally left inside the tank; cores and coils out of position; bushing assemblies distorted; wooden coil-supports at bottom of transformer burned or carbonised, due to leakage of energy, etc. Allowing a cracked or partly broken or very dirty or loose high-tension insulator bushing to go unrepaired may result in a breakdown and be a danger to life at the first wet period, and, under certain conditions of circuit connections, may cause a burn-out of the transformer windings and/or present a widespread hazard to life.

It is considered sound practice to make thorough bi-annual inspection of distribution transformers, one inspection to take place about the time the lighting and power loads overlap, and the other some time during the spring period. Tests on transformers in service are best made at a time when the transformers are passing through their heaviest service (excluding tests for determining the minimum loads). The examination of oil may or may not consist of a visual inspection to see that the oil-level is correct, and that the lid and gasket of the transformer fit properly, so that moisture cannot get inside. When a transformer has shown indications of excessive overload it should be tested and specially observed for

a time. Also, when a sample of oil is taken from the bottom of a transformer case, either by draining from the plug or by means of a sampler, it should be fully tested and the result recorded on the history card; it should receive a voltage breakdown test to see that it is in good condition; if it fails to come up to test it should promptly be replaced or filtered. Likewise for the transformer where the iron has aged due to repeated and long-period overloads; it should be replaced at the first opportunity by a more efficient unit and the aged iron scrapped.

The method of locating troubles or faults depends largely upon the apparatus used and the class of men available. "Troublemen" of equal qualifications will often attack a case of trouble differently, especially if the trouble is of a complex kind. There are no hard-and-fast rules for locating the kind of fault, although the preliminary routine is about the same for all. The same kind of trouble can occur under vastly different conditions—troubles do not in themselves arise from hard-and-fast rules—it may be of a permanent or of a transient nature. Transient troubles are not easy to locate; they may be in evidence (but not serious) for long periods before the cause is found. Although certain electricity undertakings know of (and support) the existence of certain weaknesses, they do little or nothing to find their causes and eliminate them; where there are indications of weakness, steps should always be taken to eliminate the weakness from the system.

Before the fault problem can be tackled properly, it is necessary first to become thoroughly familiar with the circuits and system; only by a thorough knowledge of the electric system can troubles and faults be located quickly. One of the methods of locating faults is by the process of elimination. Each "troubleman" develops methods in his own way, and evolves his own procedure in attacking the problems as they arise, for the particular case at the particular time, which may be during darkness or during a heavy storm or following a hurricane (troubles rarely occur during fine and peaceful weather conditions).

Every transformer taken from service to the repair shop for insulation test should withstand the standard voltage test between primary and secondary and core. If the unit has been in service for some considerable time or has been subjected to long-period heavy duty, the coils should be cleaned from sludge; this deposit impedes the oil circulation and causes the coils to overheat at a given load, which in turn increases the sediment. In cleaning, care must be taken when scraping to avoid damaging the insulation. If the transformer has broken down to the case or between

the windings, it should be scrapped. If no breakdown occurs, the unit should be given a test for core loss to see whether it should be retained in service; if the cost of the core loss in watts is higher than the price of a new unit of equal capacity, it may be advisable to scrap the faulty unit. If the unit is to be retained in service the coils should be removed from the core for a thorough cleaning and inspection, and all minor repairs made. When this has been done, the unit may then be reassembled, placed in its case and sent to the stores ready for service. The experience of many operating companies proves that it pays to rewind transformers; also that a skilled force of men being constantly employed makes it possible to handle any emergency trouble with the least possible loss of time, the minimum interruption and minimum hazards; also the general experience and knowledge of the staff are improved, and the most complicated faults and troubles are overcome with relatively greater ease to all. With foreign undertakings, far remote from the manufacturer, rewinding is a common practice; many of them dismantle, re-insulate, and rebuild.

Some of the larger electricity supply undertakings in most countries undertake transformer repairs extending from a minor trouble to a complete rebuild. As a general rule, the larger repairs are simply an assembly of laminations and coils.

If the indicated oil temperature of a self-cooled oil-immersed transformer is 80° C. or over, or, if the indicated oil temperature of a water-cooled oil-immersed transformer is 65° C. or over, the unit should be disconnected from service immediately on this discovery and the cause of the excessive heating investigated.

Temperature indicators of various kinds are in common use, some of them being ordinary mercury thermometers set into the metal fittings or immersed in the transformer oil; others are of the dial type and indicate not only the temperature of the oil but also the maximum temperature that has obtained since the last observation. These indicators measure the temperature of the windings indirectly by measuring the temperature of the oil. It is known that during periods of constant load, and constant ambient temperature, a definite relationship exists between the position of the "hot spots" in the coil and the position of the indicator in the oil, this definite relationship becoming effective *only after* the parts have reached constant temperature. On the other hand, the transformer can be subjected to destructive loads without any indication of full-load temperature. For instance, when a transformer has full load impressed upon it, and the oil is

cold, a considerable interval will elapse between the time the transformer is placed into service and the time when the oil shows signs of full-load temperature. This time-lag between the actual temperature in the transformer winding and the indicated temperature may permit operation under destructive loads if other means are not provided to eliminate it. Several means are available to deal with this; one consists of a heating coil energised from a current transformer in the main circuit of the transformer. Immediately upon taking up load, this heater acts on the thermometer element, so that it almost immediately indicates the internal temperature, and, when the transformer has reached a constant temperature, the heating coil will nearly compensate for the drop between the *hottest* spot and the position at which the indicator is located. Practically all temperature indicators are now equipped with some form of alarm to give warning when safe temperatures have been exceeded; this applies chiefly to station type transformers.

For automatically cutting out of circuit faulty or overloaded transformers, the two controlling properties are temperature and current. Temperature usually lags too far behind the current, and for outdoor type of transformers is influenced by the weather conditions. The load-current method is more reliable than the temperature method because current relays are not very delicate or difficult to keep in adjustment, and are quite accurate. Moreover, by the help of current relays transformers can be operated nearer the best over-all point of efficiency. The relays can be set at a point where the copper and iron losses of one transformer equal the total losses of two transformers, so that the most efficient point, say, to put in parallel a bank or polyphase unit will be given by $\sqrt{(2i')/(i'')}$, where i' is the iron or zero load losses of one transformer and i'' the full load copper losses. This point averages nearly 105 per cent. of the nominal rating for the transformer used, which means the banks are always cool and available for unusual demands. With temperature control there is every chance for the transformers to be overloaded and voltage regulation materially impaired; not so, however, when current relays are used and provided with full selectivity.

Moisture will usually condense on any metal if the metal is colder than the air. If transformers are allowed to operate or remain at about the same temperature as the air, or if they are colder than the air (which may be the case when taken from a cold store-room into a station or warmer room), a chance is given for failure of the insulation. Rapid and radical changes of temperature are another source of danger, for, in spite of all precautions,

moisture may be absorbed by the transformer. A good place to look for moisture is the surface of the inner top-cover; moisture may condense there and drip into the oil or run down the sides (on the inside) even when much care has been exercised in putting on and fitting the cover and gasket. The use of rubber hose for syphoning the oil gives the sulphur a chance to attack the copper.

Apart from the transformer and the connected external electric circuit, *external* mechanical troubles of various kinds develop, the most serious being those due to clogging of cooling coils and those due to the formation of abnormal pressures inside and at the top of the transformers (inside the tank or case). When a cooling coil begins to clog, this is indicated by a decreased flow of water and by an increased temperature of the oil. Dilute hydrochloric acid is probably the best thing to use for removing lime scale from the interior surface of a cooling coil; it should be made up of equal parts of commercially pure concentrated hydrochloric acid and water. At the time of making a general inspection of the interior condition of a transformer, the cooling coil may be tested for leaks. This is usually done at a pressure of from 80 to 100 lbs. per sq. in.; the pressure is maintained by means of a pump or compressor outfit or plant for about one hour and observations then made to see if it has fallen at all. With the cooling coil in position, one end is thoroughly sealed and the pressure of air maintained; water may be used where the cooling coil is not in the transformer tank.

The difficulty in relieving abnormal pressures in power transformers is largely a function of the rapidity of their formation. The transformer oil expands more, due to a rise of temperature, than any other material used in the transformer; it expands or contracts 0·75 to 1 per cent. for each 10° C. change of temperature; that is to say, if a tank contains 2000 gallons of oil at 25° C., at 75° C. it will contain about 75 gallons more. Hence the reason why the oil-level in the glass indicator rises with increase in temperature. Something like 10 cubic feet of air space in the tank are taken up by the oil at higher temperatures, and this condition brings about the increase in pressure referred to. The most serious pressures arising in transformer cases are, however, the result of arcing (and sometimes serious corona) in the oil, which causes the oil adjacent to the disturbance to be broken up into its constituent parts with a *rapid* increase of pressure due to the sudden liberation of hydrogen and other gases. Also, serious pressure rises may occur if the mixture of oxygen in the air space above the oil and hydrogen evolved from the oil is ignited by an arc; hence the present-day practice of employing "Inertaire," using nitrogen in the air space.

To relieve transformer cases from abnormal pressures, diaphragms are used, also relief devices and alarm systems.

Once per year it is advisable to open up transformers and free the oil and transformer windings from oil sludge. The causes of the sludge formation should be investigated; these include, in addition to excessive temperature, condensation phenomena and moisture in the oil. If the expansion chamber should fail (and many do fail unknowingly), trouble can be avoided by setting up an air circulation over the oil surface.

If no regular oil-testing equipment is available, tests may be made by heating a small quantity of oil in a vessel very rapidly to about 130° C. If a crackling sound is heard this indicates moisture in the oil. Another test is to put a red-hot iron into the oil; if there is a crackling sound, moisture is present.

There is little difficulty in recognising a burn-out due to continuous overload. The insulation is charred and carbonised, the oil is darkened, and there is a deposit of hydrocarbon sludge. It is always advisable to make a core-loss test before placing such a transformer into service again, because the iron loss may be excessive, due to permanent damage of the magnetic circuit.

The magnitude of mechanical damage resulting from a short-circuit is not necessarily due to the type of connections (*delta* or *star*) or the type of transformer (core or shell). A large part of it may rest with the assembly and the equilibrium of the coils. For the core type, ample bracing of the winding in the radial direction and axial coil-supports to take up any shrinkage likely to occur in the axial direction should be provided. As a short-circuit builds up, and as reflection occurs at the closed ends of a line, troubles are usually magnified at the transformer.

In station transformers which fail, the trouble is usually localised and indicates a short-circuit either due to water, lightning, excess potential, or some similar cause; usually the transformer is promptly cut out by a protecting device before the trouble has extended through the winding. In the case of distribution transformers, however, a short-circuit starting in the primary winding may, or may not, spread throughout the entire coil, depending on the way the transformer is protected. Quite often, when a short-circuit develops in the primary winding, almost destroying it, the secondary coils remain in fairly good condition. On the other hand, should a short-circuit start in the secondary winding the trouble is likely to be localised to that part, and the primary coils are rarely injuriously heated, but this will depend, of course, on the type of unit and the way it is protected. Experience seems to

show that the majority of burn-outs in distribution transformers are due to over-heating by excessive overloads, or to lightning. In distribution transformers the maximum load exists for only a few hours daily, and the tendency is to increase the maximum value of the load beyond safe limits, the transformer having fuses of such a size that several times the normal current is required to melt them.

The effect of external short-circuit is to produce enormous mechanical forces in the transformer windings, due to the short-circuit current, which may reach fifty or more times normal full-load current. The stresses imposed vary with the type of transformer. For a core type of unit, in which the centres of the high-tension and low-tension coils coincide, the mechanical stress acts in a radial direction, and, normally, the conductors themselves are sufficiently strong to resist the bursting tendency set up under short-circuit conditions. Should the centres of the high-tension and low-tension coils not coincide, an axial component of the stress is developed, which has the effect of forcing the conductors upwards and downwards in an axial direction. Rigid supports are provided for the windings to combat this tendency. For the sandwiched type of winding the mechanical forces are in a radial direction as well as a horizontal direction between high-tension and low-tension coils. If the centres of the high-tension and low-tension coils do not coincide, distortion of the coils may result on short-circuit.

As the short-circuit kVA in a large power transformer is very great and almost entirely reactive, the energy surging in the circuit is also very large. The approximate energy surging in the circuit is given by 117 (kVA/f) ft.-lbs. That is to say, taking a 15,000 kVA., 50-cycle, 132,000-volt transformer having 10 per cent. reactance, on short-circuit the kVA will be approximately ten times, or $15{,}000/0{\cdot}10 = 150{,}000$ reactive kVA. This would involve a surge between transformer and generator of approximately 350,000 ft.-lbs. of energy. This surging energy of the short-circuit is stored as magnetic flux in the space between the high-tension and low-tension windings. If the force is exerted by a uniform magnetic field, for a given energy it will vary inversely with the dimensions of the field in the direction of the force, so that the smaller the dimensions the larger will be the force. For instance, if the effective distance between primary and secondary coils in the transformer mentioned is, say, 3·5 inches, the approximate force developed is $\dfrac{350{,}000 \times 12}{3{\cdot}5} = 1{,}166{,}600$ lbs.

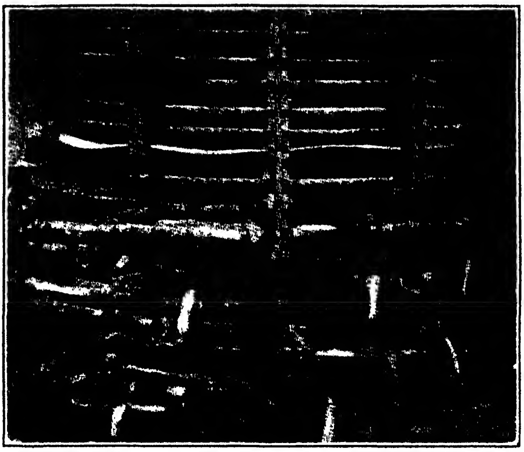


Fig. 33. Showing Burn-out due to defective Oil.

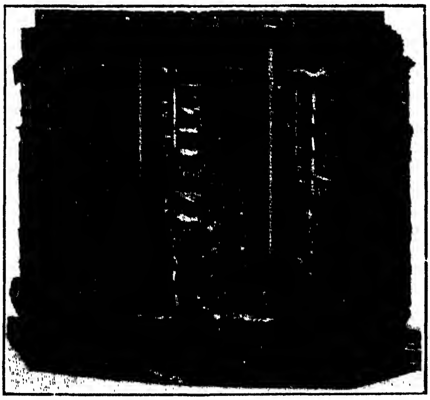


Fig. 33*a*.—Showing a serious case of Sludge.

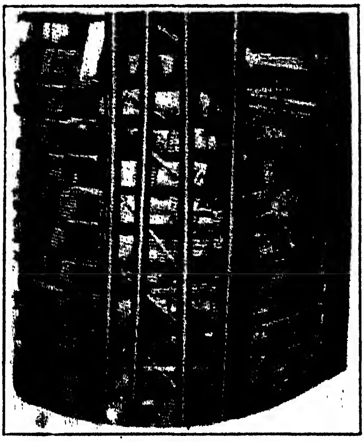


Fig. 33*b*.—Showing serious Burn-out, also slight Coil-distortion due to Short-circuit.

The most difficult of all transformer repairs are those concerned with the coils themselves. In general, close inspection will reveal a burn-out; if not, tests should be applied. Much caution is necessary in making a test. A megger or similar instrument should be used to show the condition of the insulation. A drying-out test will sometimes correct a difficulty. Inspection may reveal only a few damaged turns; these may be replaced or re-insulated, depending on the type of transformer. It may be better to disconnect all coils so that each may be independently "meggered" to the iron core (this is a preliminary test only for the purpose of locating the trouble). When it is definitely established that the transformer is burned out, then, depending on its age, type, make, etc., and the facilities for repair, it may either be scrapped, sent back to the manufacturer for repairs, or completely rewound in the company's shop.

Short-circuit between turns is the more common cause of breakdown. There are several reasons for such short-circuits, some of which are:

(1) Abrasion of the insulation caused by movement due to shock, sudden and violent overload or external short-circuit. Repeated switching operations under unfavourable conditions may also cause such a movement.

(2) Excessive vibration of the transformer on load. This vibration may result from looseness of core plates or bolts or the clamping structure. It may also cause breakdown of the insulation of the core bolts, and this will short-circuit the laminations themselves, the heat generated possibly being sufficient to distort the core. The vibration may also cause the whole iron core to become semi-solid, which condition may produce excessive eddy currents, heating, and distortion.

(3) Sharp edges of ribbon or strip conductors (which are the common types). These sharp edges, due to their weight or movement, may cut or chafe the insulation.

(4) Defective impregnation.

Transformers returned to the stores following repairs or tests should be as nearly new as it is possible to make a used piece of equipment; the shop order attached to the units should show that they have passed through the regular course of cleaning, repairing or testing, or all these operations.

Under a regulated system of tests and inspection for maximum demand-current, it is possible to operate distribution transformers well above their rated current capacity, *i.e.* the sum of the

individual distribution transformer *loads* (above 100 per cent. respectively) may be greater than the maximum station demand, and the latter may be greater than the aggregate kVA capacity of the transformers connected. Transformer burn-outs can also be reduced, and voltage drops and correct compensation for each circuit can be determined more accurately under maximum loading conditions in all sections of the primary distribution. Economical transformer operation means avoiding burn-outs due to overloads, at the same time ensuring operation during the peak-load hours as closely as possible to the maximum safe load of the equipment.

Blown fuses and other minor troubles may arise from simple switching operations. With e.h.t. systems the solidly-earthed system has given immunity from voltage troubles due to switching; but the systems are often subjected to increased current in cases of single-phase line-to-earth short-circuits. With the larger power e.h.t. systems, such as are involved in the National Electricity Scheme for this country, we may have to deal with very large currents and kVA, requiring heavy interrupting capacity in the oil circuit-breakers. To lessen the time-period of flashovers on such systems, the relay settings should be such as to decrease the actual duty on the oil circuit-breakers. The suppression of the effects caused in an oil circuit-breaker when opening a short-circuit in the network of a "super-power" system presents a difficult technical problem. The circuit-breakers must have a very high safety factor, because of the destructive capacity of stresses and explosions.

Since most faults are initially line-to-earth faults, both on the overhead and underground systems, it is now and again desirable, both to reduce local disturbance and/or destruction and to reduce the duty on oil-switches, to insert a moderate amount of resistance or reactance in the neutral. This resistance will vary with the voltage of the system and also with the extent of the system (see p. 120). Usually a very careful compromise must be made to suit best the various conditions involved for the particular case or cases (reactance is more effective than resistance).

In switching-out there is a possibility of an excessive voltage rise across the insulation if the current or the ratio L/C be large; the usual method of eliminating this voltage rise is to open the circuit by means of an oil-switch, since the circuit can be broken when the current is passing through its zero value.

Another trouble due to switching is that of high initial rush of current when switching-in a transformer on no-load. Also, when switching-in, the full voltage may be distributed over the end turns at the instant of switching. The former trouble can be limited by

the resistance drop in the primary circuit or by the addition of "buffer" resistances, which are cut out when the switch is fully closed. The latter trouble is due to the reactance and the capacity to earth of the winding; protection is given by strengthening the insulation between the turns, the end windings being so strengthened to an extent of about 5 per cent.

There are several kinds of external and internal troubles due to induced voltages. A high voltage may also be induced on the secondary (low-tension) side when an earth fault occurs on one high-tension conductor; earthing the high-tension neutral will prevent the presence of high-tension on the low-tension side, as an earth fault will produce a short-circuit across one high-tension phase and the transformer fuse will blow or the circuit-breaker trip out.

A distribution transformer failure due to lightning may be on the secondary (low-tension) side where the mains are relatively long. The hazard of the failure of a transformer due to lightning is greatly decreased by installing arresters and, when territory is covered by lines of an overhead distribution network placed in a more or less regular fashion and with the transformers also situated in a more or less regular fashion, failures and interruptions due to lightning can almost completely be eliminated by a proportioning of the lightning arrester installations in relation to the length of circuits and number of transformers to be protected.

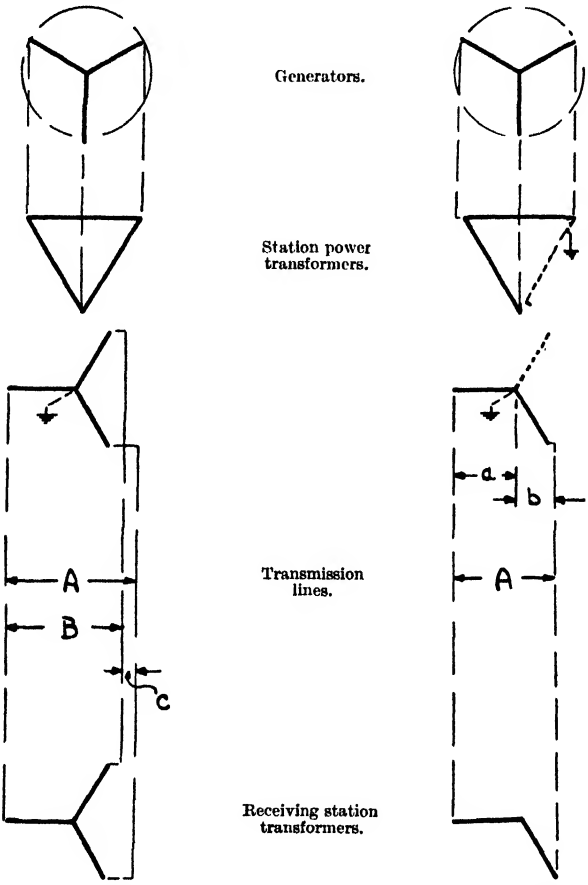
Earth faults are, without question, the most common source of disturbance. If an accidental earth holds on, the conditions instantaneously become established as a short-circuit, perhaps causing communication-circuit disturbance due to unbalanced charging current. On the other hand, if it does not hold on, assuming an unearthed system, a whole train of disturbances may be set up every time the earth strikes, and the oscillations set up, superimposed one on another, may result in very high voltages. For partly overhead lines and partly underground cables, which are the more common in practice, the hazard is increased if the neutral *is not* effectively earthed.

As compared with a three-phase core-type *star-star* connected transformer, when operating with an isolated neutral, the stress from the neutral point to earth is greater in the case of the three-phase shell-type of transformer (one of the reasons why the core-type transformer is so generally used; see also p. 37).

When a phase-winding of a three-phase *delta*-connected shell-type transformer becomes faulty, the unit may be operated in "*V*" or open-*delta* by disconnecting both the high-tension and low-tension windings of the damaged phase and short-circuiting them

upon themselves. This is possible from the fact that the magnetic flux from each phase has its own path, *i.e.* the transformer is so

FIG. 34.—Showing one of the many Dangers of *Single Earthing*, *i.e.* Earthing at the Generating Station. The earth connection is on the *star* side of the *delta-star* step-up transformers at the generating end.



(*Normal Condition.*)
A = 132,000 volts.
B = 132,000 „
C = 132,000 „

(*Fault Condition.*)
A = 228,600 volts.
a = 132,000 „
b = 132,000 „

(*This is assuming a system with the National "grid" voltage, and one earth connection as per present Regulations.*)

Note.—Instead of operating and supplying polyphase current, the whole transmission, transformation, and distribution systems are endangered and may be put out of action when trouble arises.

constructed that the phases are practically independent of each other. Hence, if one phase is faulty and it is desired to operate the transformer in "*V*" connection, the damaged phase must be

short-circuited in order to prevent the flux from the other phases taking the path which is then placed in parallel with them.

When one phase-winding of a *delta*-connected three-phase core-type transformer becomes faulty, the unit cannot be operated without removing the damaged winding from the core or open-circuiting the coils or turns to such an extent that no appreciable number of turns remains in series. For this type of transformer the three phases are magnetically interlinked and the flux from any phase has its return path over the other phases. The best practical solution for operating the unit is to remove the high-tension and low-tension windings of the damaged phase, after which the unit can be operated in "*V*" or open-*delta*. In certain countries, where a spare winding often is not available and where operation must be carried on at all costs, this and other emergency methods mentioned herein are applied to tide over difficulty and obviate loss by shut-down.

It is of some practical interest to note that a three-phase *core* type of transformer with a 3 per cent. residual voltage will produce nearly as much unbalanced earth current as a bank of three single-phase units with 50 per cent. inherent third-harmonic voltage.

With a well designed single-phase transformer having the secondary winding properly interlaced, 50 per cent. load can be taken from the middle lead and either outside lead without causing serious unbalance of voltage. For a *star-star* connected transformer, if the neutral return is arranged on the secondary winding, the unit is symmetrically loaded by connecting single-phase loads between phases and neutral, so that out-of-balance currents flow through the latter; no balance can then be obtained between the primary and secondary ampère-turns, since, on account of the primary winding being connected in *star* without the neutral point being fed from the network, the currents which flow in one phase winding must also flow through both the other phases. The result is that the various phase voltages alter considerably, and in such a manner that the voltage of the heaviest loaded phase rapidly falls. With the three-phase unit connected in *star-star*, the load on the neutral conductor must not be greater than about 10 per cent. of the normal current in the phases. Connections such as *delta-star*, "*A*," or *star*-interconnected-*star* (*zigzag*), prevent the displacement of the neutral point and thus permit the neutral conductor to be well loaded.

Transformers having one terminal earthed, such as are used on three-phase *star*-connected systems of the high-voltage types, are frequently built with the insulation graded to other windings and

earth in the order of the normal frequency voltage stresses. The danger of such a practice is shown in power transformers subjected to transient excess voltages, where voltage oscillation in the winding may raise the voltage to earth of intermediate points above the terminal voltage, unless the design of the winding eliminates oscillation.

Non-resonating types of transformers for use on earthed-neutral systems are now built in which the voltage at all frequencies distributes uniformly along the windings; the possibility of internal voltage resonance is eliminated by a proper balance of distributed capacitance and inductance of the winding. This is accomplished principally by means of conducting shields placed outside the winding and connected to the line terminal. The action of the shields is similar to that of the shielding ring on line-insulator strings. It neutralises the effect of the capacitance current from the inside surface of the winding to earth by supplying to every part of the winding a charging current equal to the discharging current of that point to earth. It is considered that the application of the shield in some cases of power transmission systems reduces the local stresses to below 10 per cent.

Table XIV.

Maximum Normal Insulation Stresses in Transformers and to Earth.

System Connection.	Maximum High-tension to Earth.	Maximum Low-tension to Earth.	Maximum High-tension to Low-tension.
Single-phase . .	0·500	0·500	0·550
Three-phase—			
Star-star . .	0·577	0·577	0·577
Delta-delta . .	0·577	0·577	0·608
Star-delta . .	0·577	0·577	0·630
"*V*"-"*V*" . .	0·577	1·150	0·645

Table XV.

Maximum Insulation Stress when One Terminal is Earthed.

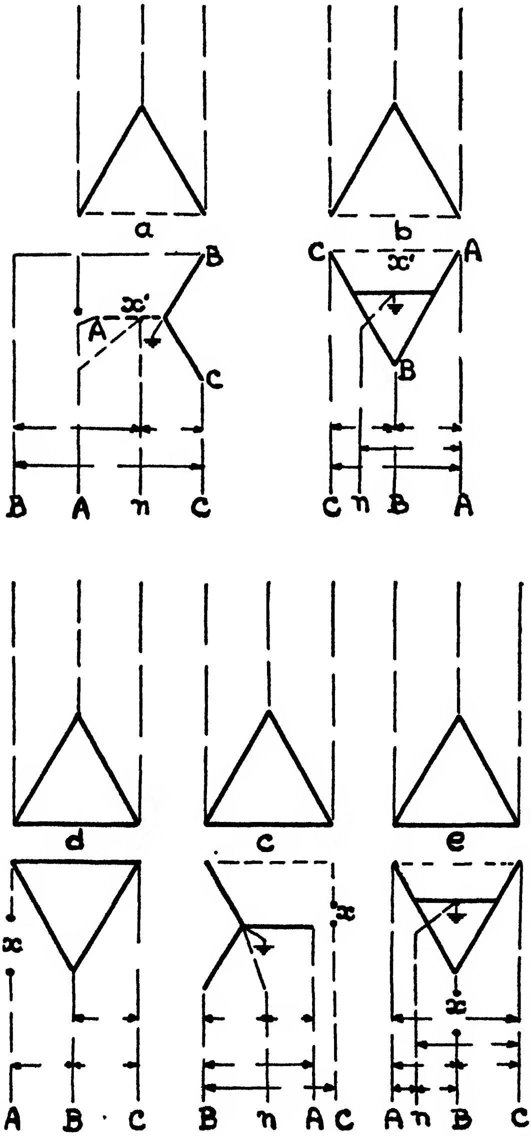
System Connection.	Maximum High-tension to Earth.	Maximum Low-tension to Earth.	Maximum High-tension to Low-tension.
Single-phase . .	1·0	3·00	0·800
Three-phase—			
Star-star . .	1·0	3·21	0·764
Delta-delta . .	1·0	3·21	0·750
Star-delta . .	1·0	3·48	0·820
"*V*"-"*V*" . .	1·0	4·26	0·866

Transformers connected to transmission and distribution systems very rarely burn out. Conductor failures are relatively more numerous, and for distribution networks they are quickly spotted when broken and promptly repaired. For extended transmission lines the case is not so simple. Moreover, the larger transforming points usually have transformers operating in parallel, which means paralleling on both sides; on the other hand, lines and circuits usually parallel to a less extent in distribution cases and consequently are much less dependent on each other at any one point, and therefore have much greater flexibility and adaptability than the transforming points. Hence the majority of connections used (whether *delta* or *star*, etc.) at the transforming points are less flexible and adaptable in times of trouble than are the lines connected thereto; especially is this so for three-phase units. As regards the best methods of transformer connection (*delta*, *star*, or "*A*," etc.) for trouble conditions, these are discussed elsewhere in this book.

When a phase-winding, or a single-phase unit of a bank of three, burns out or is faulty, the best remedy is no doubt to replace it at the first opportunity; however, local conditions may and sometimes do suggest (especially in certain countries) that an emergency method be employed. For such emergency operation we generally have the choice of using the open-*delta* and open-*star* connections or *vice versa*, and the "*V*" to "*V*" connections (the author also proposes the "*A*" method). Taking fig. 35, where one phase-unit is burnt out, it is seen that under these conditions both (*a*) and (*b*) will supply polyphase service, but lighting and other single-phase service on A phase of fig. 35 (*a*) is completely cut off. For method (*b*) both power and lighting services can be given over all three phases. Hence, where one single-phase transformer of a bank of three is burnt out, method (*b*) is from this viewpoint the most flexible and serviceable, which again shows the operating flexibility of the closed *delta* or the "*A*" connection (see p. 97).

Although the foregoing remarks cover that part of trouble due to a faulty phase-unit, far more troubles arise from the lines themselves (not the transformers) in the form of single-phase faults; the services, whether for power or lighting, are, of course, always protected by fuses or relays, or/and other means. In view of this, it is necessary to determine relative conditions for the *delta*, "*A*," and *star*-connected systems when a phase-conductor is broken or faulty. The reliability, flexibility, and adaptability of any system of transformer connection depend in the first place on the design and construction of the lines themselves. For instance,

constructing lines according to figs. 29 and 30 not only offers the highest factor of reliability against induced excess voltages, but also supplies a spare conductor for emergency operation such as may



Phase-unit burnt out.

(*a*) *Delta star* One phase-unit, A, is burnt out If the neutral point of the *star* is solidly earthed as in most *transmission* systems, the line A can be connected to it, if the solidly-earthed neutral conductor is used as in *distribution*, line A may or may not be connected to the neutral Satisfactory poly phase service can be obtained, but, for distribution lighting, one phase is cut out

(*b*) *Delta* " *A* " One phase-unit, A, is burnt out Service is carried on by the open *delta* or " *V* " connection on the high tension side, and by the " *A* " on the low tension side

Advantages The advantages are with *delta* " *A* " and *delta delta* for *secondary service*, which give lighting on all phases and service similar to the closed *delta* The *delta* " *A* " system (see fig 13) is specially favoured

Phase conductor broken.

(*c*) *Delta-star* One phase-conductor is broken The operating conditions are practically equivalent to (*a*), but, for *transmission* lines, there is the possibility of using the overhead ground wire or the continuous overhead guard wire when properly installed (see figs 29, 30) and with favourably located earths, such a modification can bring about a state equivalent to normal conditions. For *distribution* lines, such a fault is quickly spotted and repaired, failing which there is the alternative just mentioned.

(*d*) *Delta-delta* One phase-conductor is broken Such a condition leaves only one sound phase and therefore makes the system useless

(*e*) *Delta-*" *A* " For a *transmission* line, a broken phase-conductor fault may take a relatively long time to locate and repair in this case; for a *distribution* line it is likely to be spotted quickly.

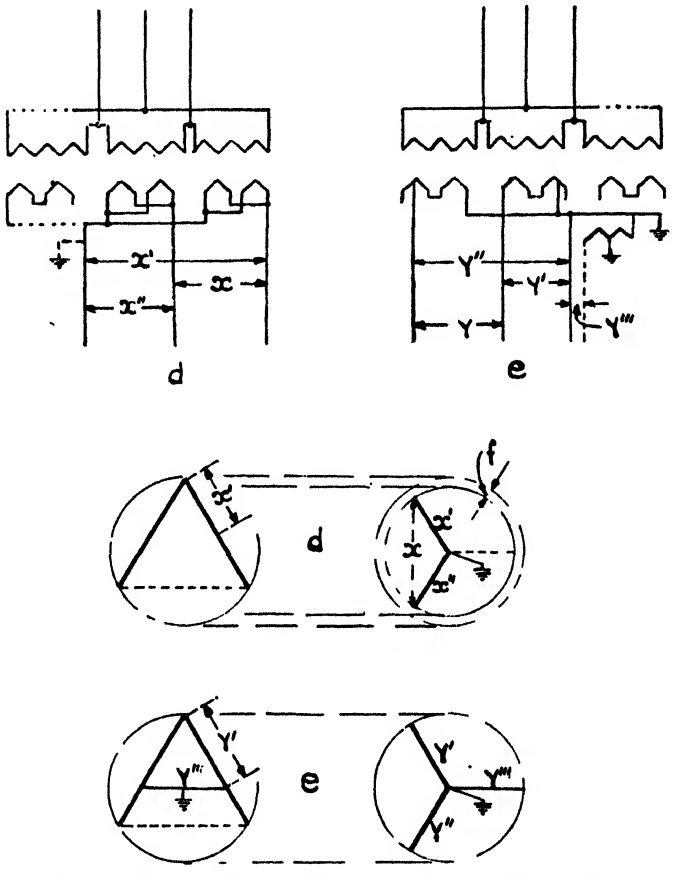
Advantages The advantages are with the *delta-star* and the *delta-*" *A* " systems for transmission lines in particular, also for primary distribution service and for secondary service

FIG. 35.—Showing Relative Advantages of the *Delta-delta*, *Delta-*"*A*," and *Delta-star* Systems when one phase-unit or one phase-conductor is disconnected for any reason.

Note.—Whenever there is a spare unit it should be connected across the terminals CA instead of standing idle.

at any time be required. The use of this construction makes various secondary systems of connections, such as the "*A*,"

FIG. 36.—Showing Maximum Possibilities for Operating the *Delta-delta* and *Delta-" A "* Systems when One Phase-conductor is Broken and Disconnected.



Note.—For (*d*), which originally was *delta-delta*, the voltage *x* between the phases is much too low, the difference from normal being that shown at *f*.

For (*e*), which originally was *delta-"A*," the voltage between the phases is the same as normal voltage. If the Y''' winding has the same ampère-carrying capacity as any of the transformers, it can be used with full advantages and safety; it may be connected up in *star* to complete the third phase when one unit is burnt out (see right-hand bottom figure). If the " *A* " method is used for e.h.t. transmission or primary distribution, the neutral point of the Y''' winding may be connected through an inductive winding to earth for the purpose of part or complete suppression (neutralisation) of the capacitative charging currents due to a fault to earth caused by flashovers, faulty insulators, etc.

entirely reliable; without its use the *delta* connection under faulty conditions is worthless, because one phase only is left (this is not so for method (*e*) of fig. 35). Hence, where one phase-conductor is broken or faulty, methods (*b*) and (*e*) are the most flexible and

serviceable and also favour the three-phase four-wire secondary system, which offers somewhat better conditions than (*a*). On the other hand, the polyphase system for (*d*) completely collapses, leaving but one useful phase. However, using the combined neutral earthed-return or/and overhead ground wire or/and continuous earthed guard wire, of proper construction as shown in figs. 29 and 30, we obtain a better system than (*b*), (*c*) or (*e*) can offer *without* it; with it these systems can continue with the maximum kVA capacity of the transformers as compared with only two-thirds of the maximum for (*b*), (*c*) and (*e*), and one-third or zero for (*d*).

From figs. 35 and 36 it will be seen that method (*e*), which system has not previously been mentioned in text-books or the technical press, is superior to methods (*a*), (*b*), (*c*) and (*d*) for both normal and abnormal operating conditions. Normally it offers the best security for suppressing the third-harmonic current in the closed-*delta* on both sides; it also provides a four-wire secondary, and sustains a true neutral point with minimum voltage to earth. Compared with method (*e*) the other systems show the following disadvantages:

Method (*a*) for *delta-star* with one phase-*transformer* burnt out. One phase for lighting is crippled; the *delta* is opened and third-harmonic current enters the secondary line; the combined load on the system is likely to become relatively more unbalanced.

Method (*b*), assuming *delta-delta* (not *delta-"A"*) with one phase-*transformer* burnt out. Potential stresses to earth are much higher; no neutral point is available; third-harmonic components are allowed to escape out on to the line.

Method (*c*) for *delta-star* with one phase-*conductor* broken. One phase has completely collapsed for lighting; should the primary *delta* be left open, third-harmonic currents pass out to the line.

Method (*d*) for *delta-delta* with one phase-*conductor* broken. As only one phase is available this method is of no further use. It may be changed to open-*star* secondary by using the 50 per cent. taps, but the line voltage is reduced and the kVA transformer capacity may be very much reduced.

Method (*e*) for *delta-"A"* with one phase-*conductor* broken and/or one phase-*transformer* burnt out. The third-harmonic current is still confined to the primary in the one case and to the secondary in the other case due to the "*A*" winding; satisfactory polyphase power and four-wire lighting services can

be supplied at a reduced output; the maximum voltage to earth is maintained at a minimum on all phases; the best relative load balance is secured. Using the line construction shown in fig. 29 or fig. 30, there is no necessity to operate with a broken and disconnected phase-conductor, since the combined earthed neutral-return and overhead ground wire or the continuous earthed guard wire may be used in place of the missing phase-conductor (the earthing of the neutral or neutrals can be made direct and solid). For transmission lines, also primary lines from distributing centres to the service transformers, the problem for the "*A*" method in particular is relatively simple and permits of suppression of the earth current, use of the most reliable overhead conductor system from the point of view of induced potentials, fixed minimum voltages to earth, together with minimum troubles due to burn-out of transformer units, and from faulty insulators and/or conductors, as well as broken phase-conductors, troubles due to birds, etc.

On the earthed systems, such as the *star*-connection with earthed neutral, the risk of fire from a momentary short-circuit to earth is usually considered very much less than from the leakage which may go on if the neutral is not earthed. When the neutral is properly earthed, the maximum voltage to earth on any phase of a three-phase circuit is only E/1·732 of the line voltage and the danger from shock is proportionally reduced. Leakage tripping devices can be used to switch off the supply when an earth occurs on any phase, so that leakage of current to earth may result in automatic isolation of the defective circuit (see p. 197).

With the *star*-connected earthed neutral system, the average insulation factor of safety is greater than in isolated neutral systems under similar conditions. An earth on the line in a solidly-earthed neutral system reduces the potential of the system with respect to earth, whereas in the isolated neutral system an earth on the line increases the potential of the system with respect to earth. Inserting a resistance between the neutral and earth increases thereby the insulation stresses resulting from line earths (see p. 113).

If a substation, installed with relatively small kVA capacity units operating with earthed neutral, is connected to an otherwise isolated neutral system with relatively large kVA capacity units, the units are liable to severe short-circuits and the earthed neutral may only partially protect the system from potential rises.

The *delta-star* connection is quite common, as will be gathered

on referring to p. 54. In case of a faulty phase-winding or a broken line-conductor, this system, together with the *delta*-"*A*" or *star*-"*A*" system, enjoys the advantage of flexibility. Provided there is a solidly-earthed neutral, this connection will operate and supply three-phase power with one secondary line-conductor and one primary phase-winding or one secondary phase-winding disabled or faulty. It is sometimes advantageous to be able to operate and supply three-phase power when one phase-unit is damaged or one phase-conductor is broken. A single-phase short-circuit on the "*Y*" secondary causes a smaller short-circuit stress than with the *delta-delta* system.

In any large network of high-tension lines it is practically impossible to continue the operation of an isolated neutral *delta* system without a shut-down (due to disturbances) when one phase of the system becomes earthed. It is possible to operate an isolated neutral *delta* system with one of the line-conductors accidentally earthed, without serious risk; but when an earth (which is very rarely a solid earth) occurs on a line-conductor an arc may result between line and earth which, on account of the fact that it is in series with the electrostatic capacity of the high-tension line, results in the accidental conditions set up generally causing an unstable arc or an arcing earth. A broken line-conductor would, as a general rule, result in an arcing earth, and experience with arcing earths on isolated neutral systems (such as the common *delta*) show that they are usually accompanied by excessive rises in potential on line and transformers, thus endangering the insulation of the entire metallic system.

Where single-phase transformers are to be connected *star-star*, a third or tertiary winding is usually provided. To avoid trouble, the tertiary winding should be connected in *delta*, no matter whether it is used or not, as neglect to do so may result in unbalanced or excessive voltages on the secondary side. The really economical and rather common type of transformer used in this country for the *star-star* connection is the three-phase core type; in this type triple-frequency voltages to some extent exist between line and neutral.

A rather common connection at the step-down end of a power transmission system is the *star-delta* connection (*star* on the high-tension side). The common practice is also to earth the neutral of the *star*. Provided there is a solidly-earthed neutral, this connection will operate and supply three-phase power with one phase-unit or secondary phase damaged, and it will also operate and supply three-phase power when one primary line-conductor or one

phase-unit (respectively) is faulty. In certain countries, where spare units are not always available just when required, this emergency connection has often served a useful and profitable purpose. The Central Electricity Board are to be congratulated on adopting this system, although it is contrary to the Regulations.

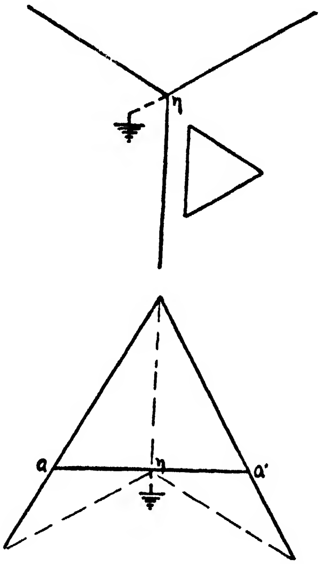
In almost any distribution system the protection must be so co-ordinated that each part will function in its proper relation to the network. The method of protection should provide for continuity of service throughout the system by detaching therefrom any transformer or circuit creating or likely to create a disturbance to the service or to the delivery of power due to faulty condition. Where there are numerous transformers scattered over an extensive network, failure of a faulty section to clear automatically may present a very awkward situation. There may be sufficient evidence from voltage disturbances and behaviour of the transformers that there is trouble on the system, but very little evidence to assist in locating the trouble. The system of protection should therefore be effective under all desired operating and weather conditions. It should be such that the "troubleman" is able to use any one, or more than one, arrangement or method of attack at short notice. The arrangement should be simple and of such a nature that all sound sections and equipment are not seriously disturbed or damaged, the faulty section can be cleared instantly and service restored almost at once; it should be reliable and should function properly. Each subsection or section should be so designed as to operate its own unit if defective, yet not interfere with or be affected by faults outside its own protected area; each faulty section should be isolated with practically no disturbance to the rest of the network.

The more the general problems are looked into, the more it is found that the crux of transformer-system problems is directly interrelated with the transformers and their connections and the design and construction of the lines and circuits themselves, as to whether they give system stability and have protective relay schemes with control of residual voltages and currents. Internal troubles with the transformers themselves rarely occur, and it has long been customary to use rather crude protective devices for nearly all sizes of distribution and service transformers; that is to say, fuses are generally considered a sufficient safeguard. On the other hand, the higher power transformer installations are equipped with automatic circuit-breakers of the oil type, and these are used in conjunction with various types of relay equipment.

With regard to the different system connections, figs. 9, 13,

and 37 show those systems in which the third-harmonic current is either absent, suppressed, or flowing out on to the line. It is becoming more generally known that the third-harmonic voltages may reach a magnitude higher than one-half the fundamental

FIG. 37.—Showing Equivalent Phase and Neutral Voltages and Equivalent Amount of Transformer Windings for the *Star* connection with *Delta*-tertiary Winding, and for the " *A* " connection.



" *Y* " *System.*

" *A* " *System.*

It is assumed that the primary side for the *star* and for the " *A* "-connected transformers is connected in *star*, respectively. Also, for the *star-star* connection a *delta*-tertiary is required to give equivalently close balance of phases, etc. on load to the " *A* " connection. The whole of the " *A* " system windings is effective, whereas the *delta*-tertiary (of the proportion shown) for the *star* connection is auxiliary to the power transformer system. Moreover, if the " *V* " system is converted to the " *A* " connection, approximately 15·5 per cent. kVA capacity is thereby saved.

(It is interesting to note that for the same line voltage and same voltage between line and neutral the same total windings are required.)

value, and that this added stress may have a considerable influence on the reliability of high-tension transformers; also that it may produce electrostatic charging of adjacent communication circuits and "dead" power lines sufficient to induce abnormal and dangerous voltage rises. This abnormal voltage condition depends on the system connections used. For instance the open-*delta* or "*V*" connection, as also the open-*star* and the ordinary *star* connection, but not the "*A*" or the *star* connection with *delta*-tertiary of fig. 37, may sacrifice the advantages of suppressing the third-harmonic current. It may be repeated, that a three-phase core type of unit with 3 per cent. residual voltage will produce nearly as much

unbalanced earth-current as a group of three single-phase transformers with 50 per cent. inherent third-harmonic voltage. This type of polyphase unit with *star-star* connection is widely used in Europe and this country.

A higher voltage system with closed-*delta* connection is rarely able to continue operation in the event of one of the line-conductors becoming *permanently* earthed at a fault, as operation will impose severe residual voltage with full voltage to earth on the other two phase-conductors. The lightning arresters may also flashover and the charging current may become very serious. For short overhead lines and relatively lower voltages, such as on secondary distribution lines, these conditions are usually not so serious. Such a system of earthing is practised very largely in the U.S.A. and Canada in order to provide an earth for lighting circuits; in the author's opinion it should be discarded entirely in favour of the "*A*" system.

For a three-phase four-wire *star* system, third-harmonic currents can flow through the different phases, through the line-conductors, and through the fourth wire from the transformer neutral. With the three-phase three-wire *delta* system, third-harmonic voltages in the different phases and different line terminals are suppressed and therefore cannot enter the line; hence the necessity for a *delta* connection. Knowing in advance whether a single-phase or a three-phase shell type or core type of unit is used, the system voltage and the size of the unit, also the practice of the particular company or country, the system connection employed or to be employed can be more or less ascertained also in advance. For the shell type and the single-phase unit it is assured that the system involves one or more *delta* connections, which means that the entire third-harmonic currents will circulate round one or more of the *deltas* (also the closed *delta* of the "*A*" system), but cannot flow in or between the line-conductors. Also, for operation when any phase-winding is damaged, the three-phase core type of transformer is at a disadvantage, and a fault will have a better chance of spreading in it than with the shell type of three-phase unit.

In connection with the three-phase core type of transformer it would seem necessary to add that, although the inherent third-harmonic voltage may amount to only one-tenth, in the case of the shell type of single-phase unit, the former type may be more detrimental to the power system and to neighbouring communication circuits than the latter type because of the decidedly safer transformer system connections favouring, and more generally used with, the latter type. In practice it is not so much a question of

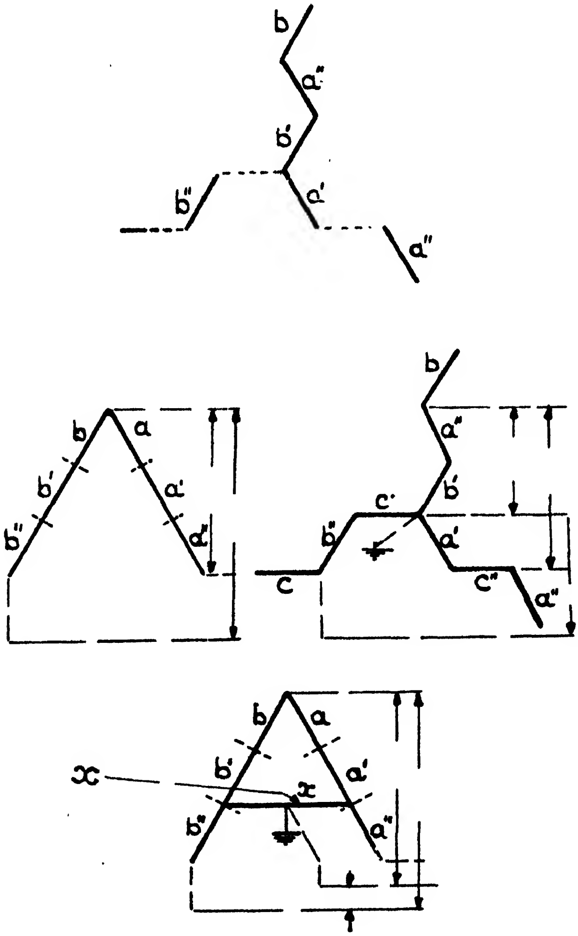
what is within as what comes out, and what is most required in this respect is suppression or complete elimination of the third harmonics within the transformer so that there cannot exist any possibility of them entering the line circuit. Without the installation of a *delta*-tertiary in the *star* connection, the common *delta* (or the "*A*") connection is the most effective and reliable system, and the most suitable type of transformer for this should be used. Independent of the type of transformer used, *all* systems should possess a closed-*delta* winding between the generator and the line, also at the receiving end of the line, not necessarily on the h.t. side. Moreover, all systems should have available a true neutral point. The best system possessing both these requirements is the "*A*" system; in fact, it is the system which helps to bridge the more common difficulties of the two principal transformer system connections, namely, the *delta* and the *star*. The "*A*" connection not only eliminates third-harmonic voltages by circulation of the third-harmonic currents in the closed-*delta*, but also permits of unbalanced phase-to-phase loads; it also provides a combined neutral point for both the *star* and the *delta*, and/or a common fourth-wire supply for both systems. In practice it also does more than this (see p. 45).

The fact cannot be overlooked that the circular coil construction of a well-designed three-phase core type of transformer offers a maximum resistance to mechanical distorting forces, the unit is inherently safer from harmonics as compared with certain other types, and it offers stability of the neutral. In so far as the transformers themselves are concerned, independent of the system of connections used, the two latter-mentioned conditions show some advantage over those obtaining with the single-phase and the shell type of transformers, but these advantages are practically negatived because the system of connections is the main and final deciding factor. Think as we please, we are simply brought back to analyse the trend of the practice we have been following for many years past—that is to say, we must first analyse and point out some of the reasons for the *insulation of all neutral points, and the attitude of the postal authorities*, on the one hand, and *multiple earthing of the neutral point* and the *attitude of telegraph and telephone engineers*, who now state that they prefer and favour multiple earthing of the power system when earthing must be adopted, on the other hand. The former-mentioned attitude and practice is truly representative of this country, while the latter truly represents American attitude and practice. What is responsible for delay and the high cost of electrical development in this country?

The three-phase core type of transformer is most suited to the

star-star connection and its best use is limited to this connection. On the other hand, the three-phase shell-type, as also the single-

FIG. 38.—Showing the reasonable Adaptability and Flexibility of the Interconnected-*star* ("*Z*") Connection and the resulting Emergency Operation with the only remaining polyphase connection (the "*A*" connection) when one phase fails.



(When each phase-winding of a "*Z*"-connected bank is split into three parts as shown, with lighting load or/and power load taken off each phase to neutral, or between the phases as shown (for power or/and for lighting), the whole of the service from the three phases may be obtained when a part or the whole of a phase-winding or one single-phase transformer is burnt out or is faulty. This is done by reverting to the "*A*" connection, as shown here. Both these systems of connections are reliable, and reverting to the "*A*" connection makes the "*Z*" connection more flexible, adaptable, and reliable for supplying three-phase four-wire secondary service for normal or abnormal operation. For *x*, an ordinary winding will serve, or a small-sized transformer-winding with voltage equal to *bb′* or *aa′*, or the spare single-phase transformer may be used.)

phase unit, is most suited to the *delta-delta* connection. The h.t. and e.h.t. *star* is a very desirable connection, and the l.t. and h.t. *delta* is an equally desirable connection. For primary and secondary distribution the principal objection, we might almost say the only objection, to the *delta* connection is the lack of a true neutral point. The type and unit to employ for distribution work in general is quite a simple problem, and, as the "*A*" system has now come into being, the only missing element of the *delta* is now provided quite independent of the type of transformer, and a wider scope of usefulness is also provided for the *star*-connected system.

CHAPTER VIII.

EARTHING FOR PROTECTION AND SAFETY.

It is generally known that a comparatively low voltage will cause severe shock or death to a person; much less than one-half the present standard secondary lighting voltage will kill. When a distribution circuit is not normally and properly earthed, an accidental earth will always produce a hazard to persons; it may also cause injurious voltage surges on the system, and is, in general, a serious operating condition on account of the increased dielectric stress set up in the distribution transformers, and installations connected thereto, and may result in possible interruptions in service.

Nearly everywhere the earth is a conductor of electricity, and, except for certain local disturbances, its conducting power is nearly uniform, because electrical potentials in the earth tend to come to a uniform value and there is no considerable resistance to stop this tendency. For this and other reasons the earth is universally considered as the standard of zero electrical potential. That is to say, every object capable of conducting electricity, if connected (or touching) damp earth is considered to be at earth potential and may remain nearly at that potential *while carrying the very small current necessary to kill a person* (see p. 197).

When a distribution circuit, which is normally earthed at the supply end, is accidentally earthed at a point on the line by a conductor breaking, the circuit-breaker at the station or supply end *may* fail to open automatically and clear the line. Possibility of contact by persons with the line-conductor or wire or other part is therefore present. On the other hand, we may also say that an a.c. circuit exposed to high-tension either directly or indirectly is not necessarily made safer by earthing on one side—in fact the circuit may be made more dangerous than it would be if kept entirely free from earth. Nevertheless, when serving many consumers, and especially dwelling-houses, the chance that the circuit can be kept entirely free from earths is so remote that generally a neutral earth connection on an installation is harmless and can

reduce or eliminate unexpected hazards from accidental exposures to high-tension circuits, lightning, crosses, etc.

A person touching an electric-lighting circuit at an a.c. voltage of 230 and at the same time any object at earth potential will be in danger. For distributing transformers the low-voltage secondary circuits which enter dwelling-houses and industrial works are close to dangerous high-voltage windings. Insulation breakdowns may occur or line-conductors or/and insulators may become displaced or broken, so that objects such as secondary installations containing sockets and appliances that are customarily handled with perfect safety come suddenly and usually without warning into contact with a high-voltage object and thus become highly dangerous. The only sure and reliable means of preventing this is by earthing, and the safest place to earth is, without question, either on or as close as possible to the point to be protected. The better the earth and the closer it is to the installation requiring protection, the less will be the possibility of loss of life or serious injury.

In urban districts, practically all electrical installations have ready access to a water-pipe on the premises. This type of earth is the best, not only because it is of low resistance, but also because it is at hand and is practically permanent in its characteristics—this cannot be said of most other earths. It is safe to connect an installation to a water-pipe system because it generally has more nearly true earth potential. A remote earth, and one of variable quality, can present a dangerous voltage at times between itself and the more perfect electrode in the dwelling, station, or elsewhere.

There are several reasons for earthing on the consumer's premises, particularly where a distribution network involves transformation, use of the same pole lines for high- and low-tension services, and stone or concrete floors, etc. Some of the reasons are:

(*a*) A metallic connection may develop between a high-tension line-conductor and one or more conductors of the secondary main or service. (If accidental contact were made to one side of the secondary main or service line in a residence and the high-tension side, a person in contact with the earth would have impressed upon him or her a pressure of several thousand volts.)

(*b*) A connection may suddenly be made between the high-tension transformer winding and the low-tension secondary winding.

(*c*) If there is an earth on the high-tension distribution feeder, and the low-tension distribution is not earthed, high-

tension voltage impressed on the low-tension dwelling-house wiring and fixtures may cause a fire or various breakdowns of insulation, as well as endanger life.

(*d*) If the protective earth is made on the consumer's premises, it becomes part of the wiring and it is therefore subject to inspection and approval and test by the government and/or supply company, and/or the contractor.

(*e*) If the protective earth is made on the consumer's premises, a multiplicity of earths from one general earthing system at almost one earth potential is provided and offers the best security.

(*f*) A person standing on the ground or coming in contact with any conducting material connected to earth might accidentally come in contact with a conducting part connected to the other side of the same secondary circuit, thus receiving for a non-earthed system either double or 1·73 times the voltage.

(*g*) Earthing the middle point of either the primary or secondary winding will prevent a dangerous voltage being induced in the secondary winding when one primary terminal is earthed. If both windings are earthed at the middle point, when a line becomes earthed the circuit-breakers should open.

(*h*) No doubt it is easier to get a shock from an earthed circuit than from an isolated circuit. Nevertheless, earthing of the secondary distribution circuits will prevent accidents to persons and damage by fire, and, to avoid any increase of potential stress between earth and low-tension installations, the earth should be well made, close to the installation to be protected, and such that it cannot be broken nor be of a value as to offer a dangerous potential difference between it and a better earth on the premises (hence the danger of one earth connection placed far remote from the installations requiring protection from the point of view of the various sources of dangerous *external* voltages, as well as protection from the dangerous *internal* 230 a.c. voltage to earth).

(*i*) If the earth is made at the supply end *only*, the earth connection at the supply end and the distribution right up to the main switch on the consumer's premises respectively, can be taken as part of the respective consumer's "protective" circuit. Since this may be of very great length it is obviously a very poor earth conductor and protector, because of the high resistance and impedance of the circuit and because of the possibility of its being open-circuited, especially at the time when it is most needed.

The *ideal* condition of maintaining earthed objects at *exactly* zero earth potential is never quite realised, because the earth connection is often not only poor and variable, but it may have to carry current and it may be of the nature mentioned under (*g*). Safe earthing is best attained and maintained by multiple earthing.

If the distribution circuit is very long, it is not necessary for any leakage to be present in order to obtain a current from any one of the high-tension lines to earth; the electrostatic charging-current for the high-tension conductors is nearly always high enough to produce a fatal shock under practical conditions. The electrostatic potential to earth may easily be of sufficient magnitude to cause a fatal shock, even though it will not operate the circuit-breaker or blow the transformer fuse in the event of an earth on one conductor. Such a condition can produce a serious hazard in the event of a cross between the primary and the secondary, if the low-tension side is not earthed, or is inadequately earthed as mentioned in (*g*). Therefore, as it is impossible to *guard* low-tension circuits and the devices connected thereto sufficiently to protect them against high tension, the surest and most positive protection is by means of earthing them on, or as close as possible to, the particular installation or service to be protected.

A desirable asset of protection is to provide sufficient sectional area in the neutral conductor — the greater the area the more effective will be the protection, because the earth will form a lesser part of the return; conversely, without neutral copper, the earth will form the whole of the return. It is therefore evident that, with single earthing, safety is very uncertain and is dependent on the dampness of the earth. In other words, if the earth at a transformer earthed-phase is absolutely dry, it is a good insulator, in which case an appreciably high difference of potential can exist between the neutral and the earth; on the other hand, if we also earth the neutral at other points such that one or more of the earth connections maintains the neutral at earth potential, there will be little or no appreciable difference between the earth and the neutral, even though the earth connections at the distribution transformer give very high resistance—hence the further safety of multiple earthing.

Earthing at the supply end only, allows leakage of primary power into the secondary circuits, and, so far as the secondary system is concerned, it is a dangerous practice. Moreover, the practice of earthing by driving pipes or/and using plate earths for earth connections is often unsatisfactory. These earth connections have very often proved ineffective in tripping out the circuit-

breaker or blowing the fuses when a phase-conductor is accidentally put to earth through a broken conductor lying on the ground. Hence the further hazard and false security of earthing at the supply end only.

The consumer should have the right to protect himself at his own expense, and the Electricity Undertaking should have the right to enforce the installation of protective measures and to inspect their maintenance, etc.

The advantages of permanency and reliability of protection, which result from the use of a plurality of earths on a given secondary circuit feeding a good-sized distribution area, will generally warrant multiple earths on the secondary, notwithstanding the possible existence of a *slight* interchange of current (which can be avoided) over those connections due to moderate unbalancing of the circuits.

The voltage rise of an earthed object is equal to the product of the earth current times the impedance. As we are mainly concerned with the secondary distribution, *for safety* the value of IR or IZ should be kept quite low. For *every location* we should not fix this or the operating voltage at 230 a.c., which is now the standard voltage for lighting circuits in dwelling-houses and factories, for this can well be a dangerous voltage. One almost sure basis we possess for measurement of voltage rise above earth is the approximate resistance of the water-pipe system, which is around 8 ohms maximum—let us say a maximum value of 11·5 ohms. We thus have two reasonably well-known values more or less fixed, namely, the voltage to earth and the resistance of the earth connection. The resistance of a water-pipe system may be as low as 0·2 ohm, but there is no likelihood of it exceeding 11·5 ohms. The general opinion is that the maximum voltage rise of any earthed object above earth potential under any condition should not be greater than 115 volts; this requirement is well met by earthing at or on the particular installation to be protected.

Practically every country has adopted almost exclusively the use of three-phase transmission, and it is quite evident that, when judged from every viewpoint, there is no better system available for present-time requirements. On the other hand, in so far as the transmission line in particular is concerned, the writer firmly believes that proper use is not made of it; *i.e.*, all possible insulation should be retained and the neutral should be made use of for increasing the protective value of the system from all kinds of external pressure rises, etc., for increasing the kVA capacity of transmission in terms of equal voltage stress to earth, for increasing

the operating value, and for permitting a more reliable line should a line-conductor or/and a transformer phase-unit fail; this also means a better earning-power line. Independent of the system used, the writer is quite convinced that overhead electric power lines are not being used or designed in the right manner.

A transmission line and system requires and should provide, for equal transmission distance and equal stress on insulation, the highest possible kVA capacity, the greatest inherent protective value, and the maximum reliability for normal as well as abnormal conditions—the abnormal conditions with proper design and use being different from and much safer than those with present-day design, construction, and operation.

What applies to transmission lines generally applies to distribution lines, but the latter are differently insulated, have many taps and branches, are more liable to earths, are worked-on the most, carry heavier currents, require greater care for copper economy, have smaller allowable voltage drop, and so on.

For the distribution, single-phase three-wire and three-phase four-wire (with neutral earthed in each case) should be the general rule. For equal voltage to earth, *i.e.* equal maximum stress on the insulation, there arise many advantages for the earthed neutral systems. For normal operation the merits of the various systems are well known; sometimes the *delta* connection is compared with the *star*, and at other times the isolated neutral system compared with the earthed neutral system, and so forth, showing in each case certain viewpoints as to economy or operating advantages. No doubt the best comparison is to assume normal operating conditions in the one case, and then compare abnormal operation for equivalent requirements.

For normal operation and equal maximum stress on the insulation, the merits of the earthed neutral symmetrical systems, for distribution lines in general, are decidedly favourable to relative economy or total conductor proportion for equal distance of transmission and power delivered, etc.

For abnormal operating conditions of the isolated neutral systems (assuming an accidental earth on any one phase-conductor), the factor of safety is reduced 50 per cent., the unbalanced current is more likely to cause noticeable inductive interference, the resulting arcing earth may quickly endanger insulation on other parts of the system, and, when compared with normal operation of the earthed neutral systems, relative total conductor costs and their annual expense factor are greatly increased; furthermore the hazards may be greatly increased and operation similarly impaired.

An earth on the latter systems may result in a short-circuit on the earthed phase and a shut-down unless provision is made to supply polyphase current and operate over the remaining phase-conductors and neutral conductor; this latter practice is sometimes followed. It is certainly better than the open-*delta* with an earth on one phase, but is not quite so good from the operating viewpoint as the closed-*delta* with an earth on one phase. It is, however, necessary to bear in mind that for equal voltages to earth the *star* has a kVA capacity of transmission nearly three times that of the *delta*.

Distribution systems are more generally connected as shown in fig. 39 (2) and (6) or (3) and (5), where the neutral is earthed. If connected as shown under (1) and (7), and there is an accidental earth on any one line phase conductor, then for equal maximum stress to earth as compared with (2) and (6), the total amount of copper required is *four* times more for (1) and *three* times more for (7); the earths shown in (1) and (7) in each case represent earth faults on one phase-conductor.

For secondary low-tension mains in particular, we also have a choice of (3) and (5) when the neutral is earthed, where *E* is the voltage from neutral to line phase-conductor. The values given show the relative amounts of copper required to deliver the same kVA the same distance for the same delivered voltage *E*.

For equal effective voltage the relative current per phase-conductor, relative voltage between phase-conductors, relative loss per phase-conductor, and total relative weight of phase-conductors for the single-phase and the three-phase systems, *are the same*; and, for the same effective voltage to neutral, all systems have the same copper efficiency. The copper efficiency of the single-phase and the three-phase systems, based on effective values, is given as:

	Single-phase.	Three-phase.
Voltage between phase-conductors .	100 per cent.	100 per cent.
Current per phase-conductor . . .	100 ,,	57·7 ,,
Loss per phase-conductor . . .	100 ,,	66·7 ,,
Relative total conductor weight . .	100 ,,	75 ,,

Of all the different factors involved, for a given length of line, the current in ampères is one of the most important affecting voltage drop. It may be desirable to start with that system allowing of the greatest kW load per ampère transmitted. This favours the *three-phase four-wire* (*star*) system, which will transmit the greatest kW load, and requires less total relative weight of conductor per kW transmitted, for equal voltage to earth, than

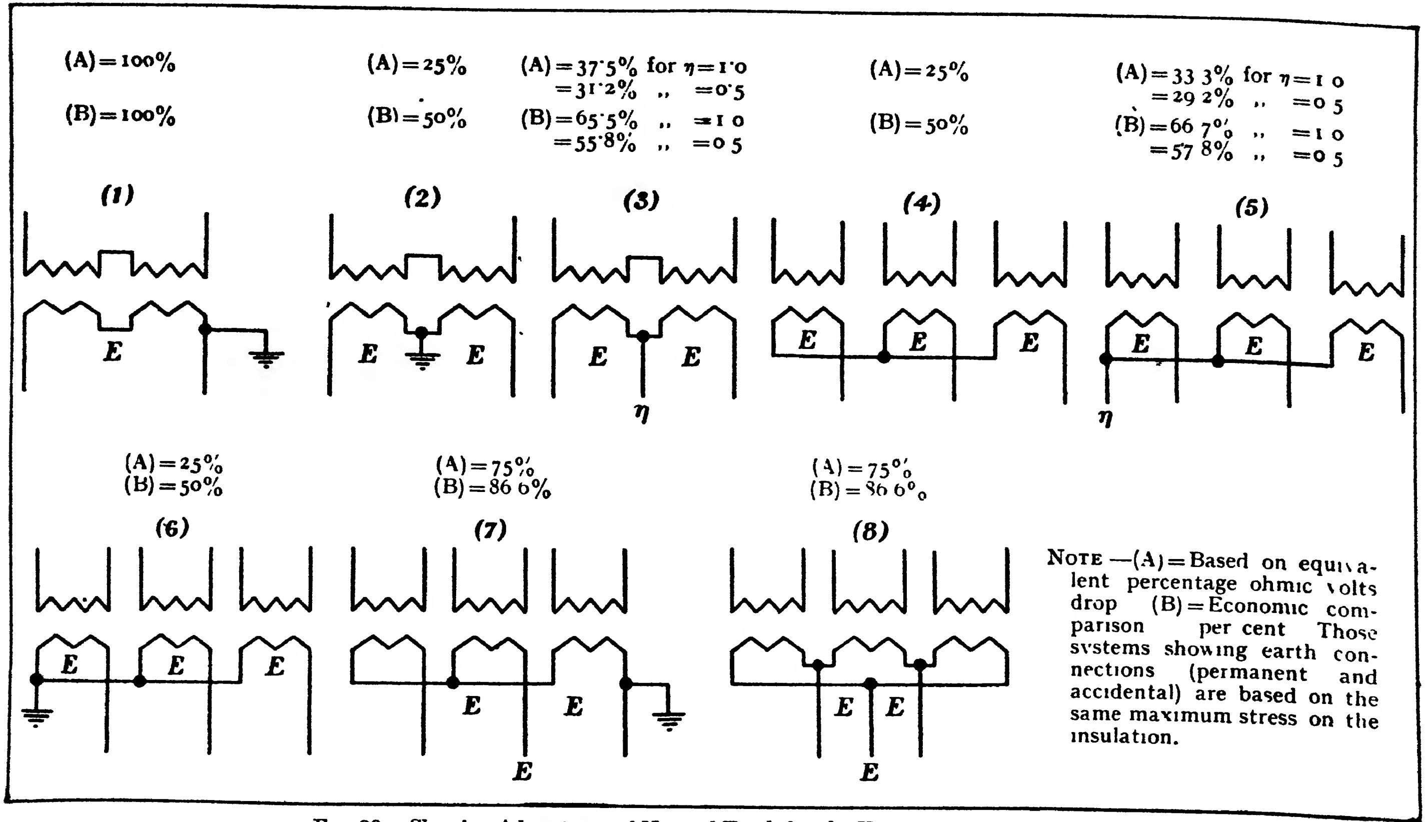


FIG. 39.—Showing Advantages of Neutral Earth for the Various Common Systems.

other a.c. systems; and, the cheaper the line conductor, the less likely we shall be concerned with the weight-cost but the more we may be concerned with a smallest line current for a given kW transmitted; also, the most important question may be that of total line loss.

It is one thing to deliver three times more power, and it is another thing when this can be done for one-half of the line loss, and with the greatest flexibility and reliability. Hence the necessity of knowing that the *best* system is the three-phase four-wire ("*Y*," "*Z*" or "*A*"), and the *second best* the single-phase three-wire.

The relative values given in Table XVI apply to the various classes of conductor metals, but more particularly to the copper and the aluminium line; the a.c. power loss for a steel conductor is, of course, made up of the d.c. resistance, the skin-effect resistance loss, and the hysteresis loss.

Table XVI.

System Values for the Same Current Density.

Conditions.	Single-phase.		Three-phase.	
	Two-wire.	Three-wire.*	Three-wire.	Four-wire.*
Relative Voltage.	E	E / E	E / E	$\sqrt{3}E$ / $\sqrt{3}E$ / E
Relative kW transmitted per ampère . . .	1·0	2·0	1·732	3·0
Relative total weight of conductor	1·0	1·5	1·5	2·0
Weight per kW transmitted	1·0	0·75	0·866	0·666
Relative percentage loss .	1·0	0·5	0·866	0·5

* Balanced load. Neutral conductor is of the same cross-section as the outers.

In fig. 40 are shown voltage vectors and phase relations for different polyphase systems:

(A) Symmetrical two-phase five-wire system—sometimes called a *quarter-phase*, and on rare occasions called a four-phase five-wire system.

(B) Showing the "*T*" or *Scott* system compared with (A); the maximum voltage to earth is the same for (A) and (B) systems.

(C) Showing the "*Y*" or/and the three-phase–two-phase

systems of fig. 46, compared with (A); the maximum voltage to earth for the "*Y*" system is the same as with (A), but the other systems show a slightly higher maximum voltage to earth as compared with (A).

(D) Showing the conversions of the *Taylor* systems of fig. 49

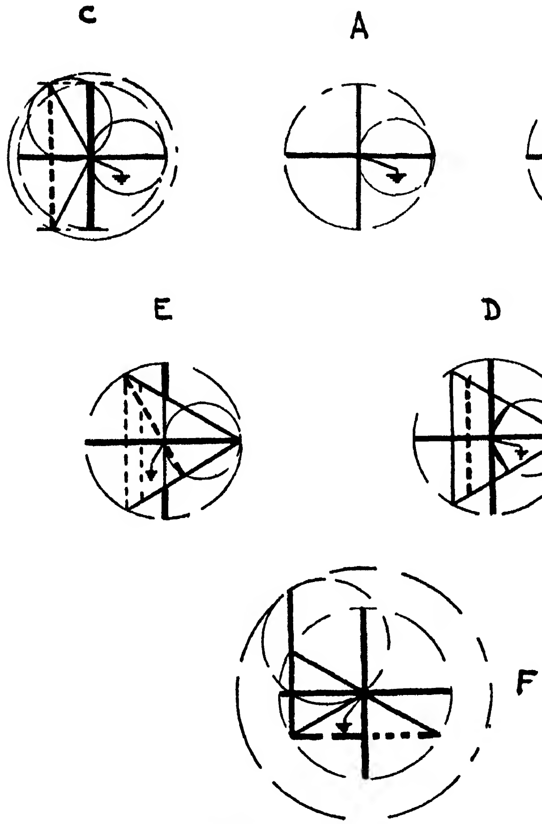


FIG. 40.—Showing Relative *Maximum* Voltage to Earth for the Different Polyphase Systems—taking the Earthed-neutral Two-phase Five-wire System (A) as a Basis of Comparison.

and fig. 50, compared with (A); the maximum voltage to earth is almost the same in every case.

(E) Showing the "*V*" or open-*delta* system converted to the *Taylor* system of fig. 13; the maximum voltage to earth is the same in every case (see fig. 50).

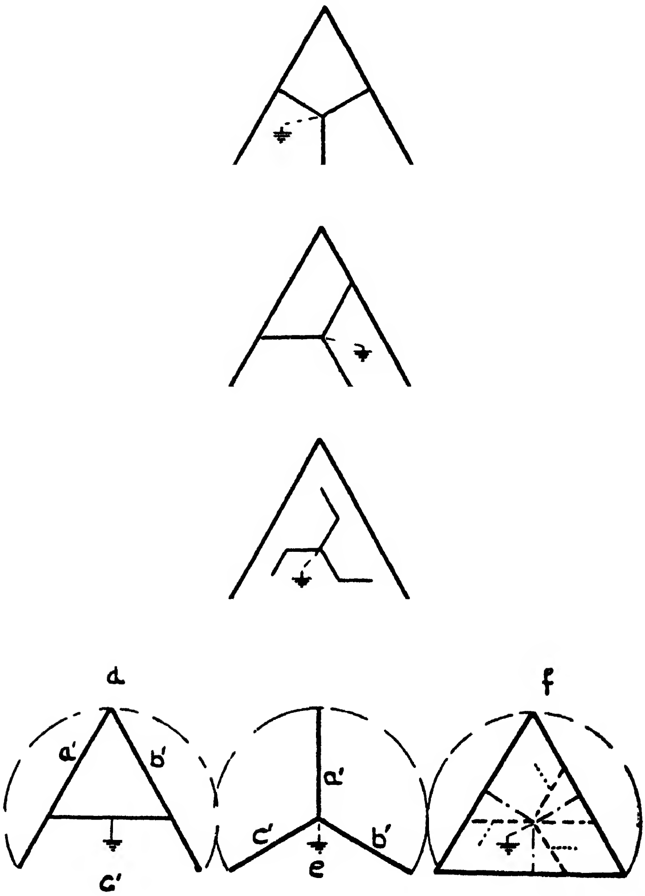
(F) Showing another three-phase to two-phase system, compared with (A); the maximum voltage to earth is seen to be much higher and disproportionate as compared with (A).

In a distribution system the lines and equipment are scattered over a large extent of territory and the energy supplied to respective dwellings is relatively small, hence the number of persons likely to come into contact with switches, lamp-holders, plugs, and house appliances and equipment, is very great, and any deficiencies in the earthing on such widespread systems may have serious results. The cost of the installation of earths on consumers' premises is but a very small part of the total wiring cost, and it need not enter into the matter of cost to the supply undertaking. For overhead distribution in particular, the author recommends that the secondary neutral of every house service be earthed on the service as well as at the distribution transformer for greater safety in case the earth lead becomes broken, and also to improve the general earthing of the system and circuit for best protective purposes. In this way, excess voltage cannot enter the premises and a dangerous difference of potential between the neutral of the service and the earthing objects in the house cannot exist.

Where dwellings are furnished with water meters, the meters should be permanently jumpered across by a strap or cable where connection to the water-pipe is made on the house side of the meter. Where possible, earth connections should be made on the water main side (before the water meter) so that the earth circuit is never disturbed when a meter is removed.

A possible disadvantage in earthing the neutral of a three-phase four-wire system is that a break in the neutral with unbalanced loads will result in serious unbalanced voltages, assuming that the earth is made at the supply end *only*. If a single secondary earthed neutral is used, then it should be earthed at some point (or points) on the distribution network. Earthing at the substation or at the primary feeding-points of the distribution will provide a certain amount of lightning protection. A short-circuit between phase and neutral may raise the voltage of the neutral above earth near the point of short-circuit owing to the impedance drop in the neutral (fourth wire); this condition may cause an increase in voltage on the other two phases of the order of two or three times normal voltage. To overcome these disadvantages the neutral should be earthed at the substation and at other points of the system as mentioned. For any extensive neutral system, such as the three-phase four-wire distribution system, in order to keep currents from flowing in the earth, the neutral system must have a very low distributed resistance, and multiple earthing best provides for a very low and evenly *distributed* resistance not obtainable in any other way. If the neutral conductor should open between

FIG. 41.—Showing the Various Earthed-neutral System Connections.



(*a*) Tertiary-" *Y*," each phase-winding of which is connected at the centre point of each transformer phase-winding.

(*b*) Tertiary-" *Y*," each phase-winding of which is connected at the 66·7 per cent. point of respective units, giving the same advantages as (*a*), and also, should one phase-unit burn out, operating as shown in (*d*) by using the two remaining legs of the tertiary.

(*c*) Tertiary-" *Z*," each phase-winding to be connected symmetrically at any desired point of the respective phase-winding.

(*d*) " *A* " connection, showing a winding connected at the 66·7 per cent. point of the two phase-windings.

(*e*) " *Y* " connection, showing value of (*d*) when one phase-winding has burned out. If the current-carrying capacity of the tertiary is large enough, then (*d*) offers the best all-round connection for normal and abnormal operating conditions.

(*f*) Shows combination of (*a*), (*b*), (*c*), and (*d*).

Note.—All these windings of the earthed-neutral systems have some damping effect on earth currents, short-circuits, telephone disturbances, unsymmetrical loading, discharge of static charges, etc. Using a high impedance winding is especially helpful in the suppression of earth current, and placing a high impedance winding between the tertiary and earth will help to compensate the capacitative charging currents at the fault to earth, which latter may be due to a flashover, faulty insulator, broken conductor, or fault to earth on some part of the network. The system connection (*d*) is a simple conversion of the open-*delta* to give both *star* and *delta* on the secondary with true neutral point.

the transformer and the load, an unbalanced load on the phases would cause an unbalance in voltage, which might be disastrous to lamps burning in the circuit at the time. The most satisfactory method of overcoming this danger would likewise be that of earthing the neutral not only at the substation or distributing centre but at a multiplicity of places on the distribution system. The earth connection would serve as a path in parallel with the neutral conductor, and if the neutral conductor broke anywhere, the earth would take care of the unbalance load and prevent damage or danger.

In view of the outcry (by those[1] who should know better) against multiple earthing of systems in this country, it may be taken that one of the most *forward* steps of modern times is the multiple solid-earthing of the 132,000-volt National Electricity Scheme.

It is of special importance to note that a close balancing of phases is essential to the most satisfactory operation of the earthed neutral or earthed conductor systems. In the U.S.A. and in Canada and certain other countries, it is common practice to earth the *delta* system as shown in fig. 13 (2), using four, six, or even seven wires, as shown. The *delta* system is, no doubt, better than the *star* or *zigzag* for maintaining a close balancing of phases and currents, but it does not possess a true neutral point. To overcome these disadvantages of the *delta* and the *star* systems, the "*A*" (combined *delta-star* primary *or/and* secondary) system has been devised by the author.

Transformer secondary service neutrals and the distribution neutral can often with advantage be connected to the same conductor or wire and earthed at the transformers, giving the net result of a large number of earths in multiple. The total resistance to earth of these neutral conductors is almost invariably low. The neutral wire may thus form a valuable earth circuit for station earthing and should for best results always be connected to the station earthing system. Thus a direct metallic return to the transformer neutral is obtained, which, to a large extent, relieves the station or transformer earthing system from carrying unbalance or fault current.

After an earth has been installed on the neutral conductor of the 400-volt secondary main, an approximate value of the resistance can be obtained by connecting a suitable fuse to a wire attached to the water-pipe system, and another wire to one of the secondary mains; the two free ends are then momentarily brought together when ready. *For example*: Considering a 400-volt four-wire

[1] See *Engineering*, p. 243, 22nd February 1929.

secondary main, if sufficient current flows to blow, say, a 20-ampère fuse (400/20 = 20 ohms), the earth connection may probably be considered satisfactory. This method of measuring is used only where instruments are not available.

For this country, lighting circuits are limited to a pressure of 230 volts to earth. The danger in handling faulty lamp-holders, frayed lamp-cords, and defective house appliances of various kinds for normal conditions of service is therefore limited to 230 volts to earth; this voltage cannot be considered safe to life. Also, uncertainty exists with the earthing or isolating method and connection, the house fittings and appliances, etc., and the efficiency and location of the earth. Adequate earth resistance depends on the circuit voltage and the kVA capacity of the transformers, and hence it depends on the type of electrical installation. Roughly, the resistance (or impedance) should be such as to prevent the 400/230-volt secondary circuit from becoming charged with high-tension voltage through, say, an impressed or an induced high voltage or the breaking down of the insulation of the transformer windings. However, it is to be understood that the secondary circuits would still be charged with high-tension current if the primary and secondary circuits became crossed and/or an earth occurred such as, for instance, a cracked insulator on the high-tension circuit. In this case the high-tension station fuse or circuit-breaker should operate automatically and the resistance of the earth connection should be sufficiently low to cause the blowing of the fuse or tripping of the circuit-breaker (see fig. 44, p. 196). To afford ample protection, the earth resistance in all cases (where a water-pipe cannot be reached) should be kept as low as possible, as the earth resistance obtained by driving pipes and plates into the ground is particularly liable to change with weather conditions, owing to difference in moisture of the ground, etc.

There are several reasons for earthing a secondary distribution, but one of the chief reasons is that of preventing, under accidental conditions, the maintaining on the secondary circuit or circuits of a voltage in excess of the normal operating voltage. A 15-ampère flow of current through an earth resistance of 11·5 ohms will require 173 volts impressed on the circuit. Not only is it essential to *reduce* this voltage, *i.e.* make the resistance as low as possible, but it is hardly less important to have one side of the consumer's lighting service at almost the same potential as the earthed metal parts of switches, lamp sockets, and connected house apparatus with which a person may come into contact at any time. This can be best attained by earthing on the consumer's premises, and

wiring and working the appliances as mentioned later, which practice also avoids any possibility of dangerous voltages due to induced excess voltages or the accidental crossing of higher voltage line wires with the house service leads.

The chief reasons for earthing the secondaries are therefore evident from the foregoing discussion. The liability of a very high potential in the secondary distribution as the result of an induced voltage due to a primary conductor earth or as a result of contact with a high-tension system due to broken and crossed wires, is very much greater than the liability of high-tension on the secondary distribution through the failure of the high-tension insulation in the apparatus. If high potential gets on to the secondary 230-volt distribution it is apparent that it may cause a breakdown of the secondary distribution insulation somewhere and do much damage; perhaps the primary fuse of the distribution transformer will blow and clear it, perhaps it will not. If the secondary is properly earthed, the fuse is sure to blow and clear the trouble, hence the best protection is secured by multiple earthing.

In times of trouble the normally unearthed system may become earthed on any phase-conductor and conductors may cross. In consequence, the lineman responsible for clearing the trouble may be exposed to the maximum voltage possible, because of a combination of crosses and earths, and under circumstances of excitement, storms, and darkness, the danger may be very great. In the design of a distribution system the first important consideration should be the life hazard. With a normally-earthed system, circuit and service, no abnormal voltage conditions can exist, for accidental earthing of a phase-conductor is not so apt to weaken or burn-off by arc formation, and the damage is not liable to be so great or the duration of the interruption so long. In view of the existing standard secondary voltage of 400/230 and the Rules for the "Safety of the Public," we may ask the question: Can we fix a *safe maximum voltage* at which accidental contact would not be dangerous to life? This question is very broad, because it involves both normal and abnormal operating conditions as well as *location* considerations; nevertheless it is fully answered in this chapter.

Until recently, this country has been classed as an 85 per cent. direct current and a 95 per cent. underground cable country. The not very distant future will assuredly see this country an 85 per cent. alternating current country with networks of overhead lines spread over rural and urban areas. With these long-overdue changes will come changes in ideas and practice from the present underground cable practices and methods, and with the change

to *overhead* networks will surely come greater danger to life. As one illustration we may take the simplest two-wire primary and secondary erected on one pole line. If one high-tension primary conductor should become earthed or come into contact with the low-tension secondary, it is doubtful if the distribution transformer fuses would blow, in which case the voltage on the secondary would become much greater than 230 volts, and the life and the fire hazards would be great; furthermore, there would be no indication anywhere (unless directly visible) that the high-tension was earthed through a cracked insulator or in contact with the low-tension main or service leads. By solidly earthing the neutral point and solidly earthing the low-tension secondary, should metallic contact be made between high-tension and low-tension circuits, the high-tension fuses will either blow or/and the trouble will immediately be indicated at the distributing centre or station; in any case the maximum low-tension voltage will be limited to a maximum of 230 volts to earth by service earthing.

If the low-tension secondary (due to not earthing services) is free to take up for a moment a voltage above earth approaching that of the high-tension primary, a very dangerous condition will exist. If a person should come into contact with the low-tension secondary a path to earth will be provided and a fatal shock will probably ensue; in the other case, as the insulation of cables and wires in buildings and dwellings is very rarely designed for the high-tension voltage, its breakdown may start an arc, then a fire. If the low-tension services are properly earthed, these dangers cannot possibly exist.

Practically the whole danger problem is connected with the people in dwelling-houses and industrial works because of the enormous number of persons involved in the handling of plugs, holders, switches, etc. At the present time something like 2,000,000 houses in this country are wired for electric lighting. We therefore have every reason to concentrate attention on what can happen with and without induced high potential or if the high-tension line or/and transformer-winding make metallic contact with any part of the low-tension secondary. In certain areas and countries, such conditions are possible every time a high wind or a lightning storm occurs.

Who can say that it cannot be claimed a criminal act (the responsibility for which rests upon those specially trained and paid to know) to send an unskilled worker into, say, parts of a colliery or the inside of a wet water-tube boiler with an unearthed portable hand-lamp in his hand, the lamp working at a mean pressure of 230

volts to earth under normal conditions of operation? If this is a hazard to life, why is it not equally as criminal to expose every lamp-holder, switch, etc. to the possibility of a very much higher voltage to earth? No one can dispute the fact that secondary mains and house wiring are liable at any time to high-tension current caused by one or other of the accidents mentioned herein. We may well ask ourselves the question: Shall we specialise on the best means of protecting life and property, or shall we continue to give preference to inductive interference of communication circuits? As shown herein, *location* decides the secondary voltage, etc.

The greater the possible voltage difference between metallic casings (such as lamp-holders, plugs, flat-irons, etc. in dwellings, offices, and works) and the earth, the greater will be the danger to life; in like manner, the greater the network and/or the more remote the earthing point from such dwellings, etc., the greater will be the danger to life. In line construction all sorts of devices are used to touch and perhaps catch a broken wire on its way to the ground or to earth, with the idea of holding it out of the reach of possible passers by; yet the same distribution system will expose every person in every consumer's dwelling to far greater risk to life as well as provide the risk of setting fire to the dwelling, etc.

If it is desired to limit the potential stresses at fundamental frequencies to 57·7 per cent. for a three-phase *star* or "*A*" or "*Z*" connected system, then the *allowable practice* of this country provides for the following:

(1) Where the step-down transformers have about the same kVA capacity as the step-up transformers, earth at the sending end *only*.

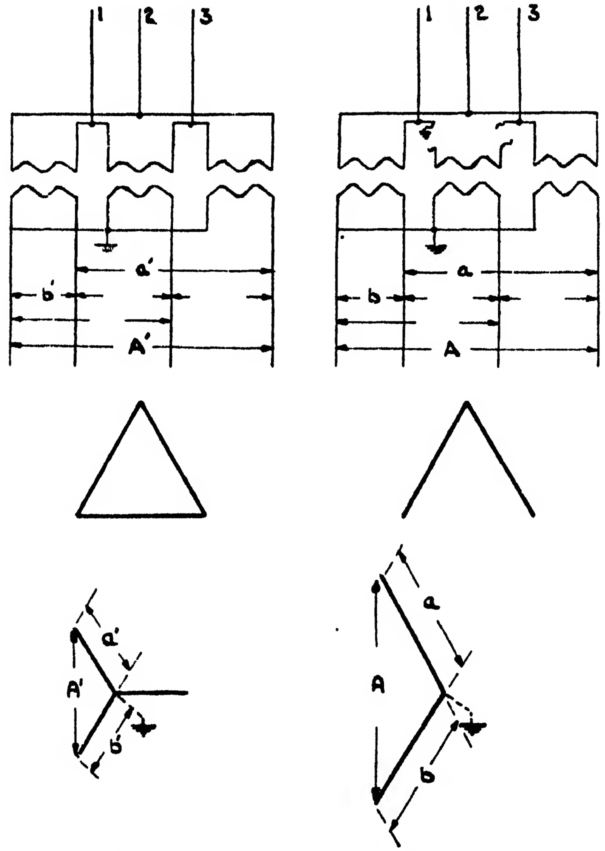
(2) Where there is the ordinary transmission line or primary distribution system, earth at the sending end *only*.

(3) Where there is a large distribution centre and relatively much smaller distribution transformers scattered over considerable territory, earth at the sending end, and when approval is given, earth at each distribution transformer.

For *best* protection we should have a direct and properly multiple-earthed metallic return from the consumer to the station or transformer. This largely relieves the transformer or/and station earthing from carrying unbalance or fault current; in other words, it tends to relieve the station and transformers from possible dangerous potential rises. The latter conditions are quite probable at certain points of the distribution system; hence the advantages of multiple earthing. For a low-tension three-wire network, the

neutral need not be earthed in the substation; it may with advantage be earthed somewhere on the network.

FIG. 42.—Showing Danger of *Delta-star* Connection where Generator Neutral Connecting Leads 2 and 3 is not Earthed and where the Fault shown occurs on the Transformer Unit.



(*Normal Condition.*)
$a'b' = 230$ volts.
$A' = 400$ „

(*Fault Condition.*)
$a = a'\sqrt{3} = 230 \times \sqrt{3} = 400$ volts.
$b = b'\sqrt{3} = 230 \times \sqrt{3} = 400$ „
$A = a\sqrt{3} = a'3$
$= 230 \times 3 = 690$ volts.

Note.—It is quite possible to connect up a transformer with a loose contact (nut or terminal) at the connection or terminal-board, and, due to bad contact, provide for either a complete roasting-up of the whole installation, or the lead burning loose and dropping by gravity to make contact with the earthed transformer case or tank. For a wood pole installation, especially where the oil has been allowed to sludge and badly carbonise, a fire may occur and burn down the whole structure, apparatus, etc.

For this country it has been laid down that: "when any e.h.t. (6600 volts and above) circuit is connected with earth, the connection shall be made at *one point only*, namely, at the generating

station, or substation, or transformer, and the insulation of the circuit shall, except at that point, be efficiently maintained throughout. Also, the neutral point of the *star*-connected winding of each distinct three-phase circuit used for e.h.t. may be connected with earth, *or may be insulated.*" With regard to the earthing of the e.h.t. system or circuit, this is done for protection of the system or circuit. As the pressure is too high, earthing cannot give protection to life. For the secondary pressure of 230 volts, however, it is an entirely different matter, and multiple earthing enters upon a phase of great importance.

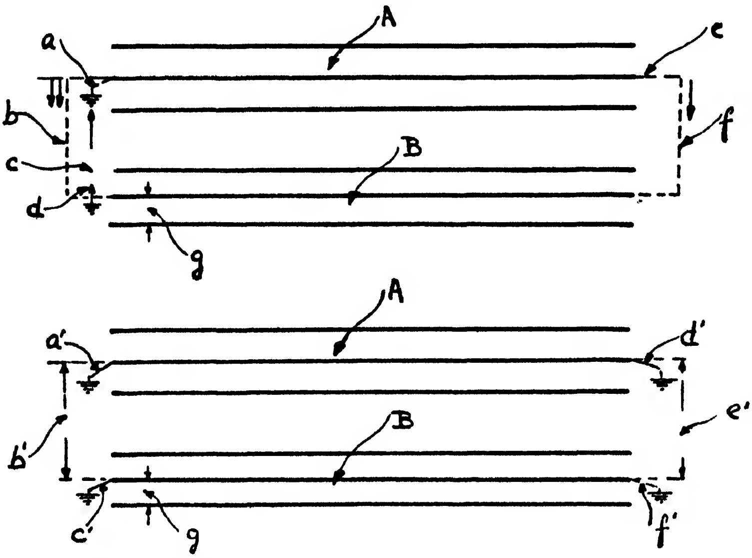
On the earthed system the risk of fire due to a momentary short-circuit to earth is usually considered very much less than the risk due to the leakage which may go on if the neutral is not earthed or is inadequately earthed. Leakage tripping devices can be used to switch off the supply when an earth occurs on any phase, so that leakage of current to earth may, or may not, result in automatic isolation of the dangerous or/and defective circuit. A current small enough to kill, however, may affect the most sensitive tripping device but little. The solidly-earthed system or circuit is the most positive in action.

An earth on an unearthed neutral system or circuit does not necessarily constitute a short-circuit, yet, due to the capacity of the line and the inductance of the system, the non-permanent earth may cause a charging current to oscillate with the voltage, and the voltage may be built up, and the disturbance continue for some time, following the earth make-and-break contact. This oscillation of the charging current and the voltage will produce a series of arcs at the point of earthing. These may accumulate and build up voltages many times normal and may result in flashovers or insulation weaknesses or breakdown in transformers at several points of the affected system, thus producing short-circuits of a far worse nature than would an earth on an earthed neutral system, and particularly on a multiple-earthed system.

An earth on an earthed neutral system or circuit will result in a short-circuit and a large current will flow, but the impedance of the circuit and transformer is in series with the gap and will tend to stabilise the current, making it impossible for the arc to make and break as occurs with the unearthed neutral system or circuit. Earthing the neutral also tends to localise and limit the fault to one point. For a distribution centre, and distribution supply in general, it is best to earth the neutral *solidly*, because a path is then provided for enough current to pass for positive relay action when a fault occurs, which latter is (or may develop into) a high-resistance

fault. Hence the necessity of multiple earths for improving the earthing of the circuit, *i.e.* earthing the secondary neutral at each transformer *and* on each service, as shown in fig. 43.

FIG. 43.—Showing Example of Hazard from Voltage Rise Above Earth Potential due to Earthing at the Supply End Only.



(Showing hazardous condition.)

(Showing safe condition.)

A. *Primary Distribution System.* (Carrying between 30 and 100 ampères on the usual 11,000-volt line).
B. *Secondary Mains and Service System.* (Normally at 115 or 230 volts to earth.)
a, *a'*. Station or distributing centre, with earthed neutral 5–10 ohms resistance.
d. Contact of earth with house fitting through person.
b'. No earth-current flow.
b. Possible dangerous earth-current flow.
c. Possible dangerous potential rise above earth.
c'. Permanently established earth connection on all non-current-carrying fittings to water-pipe, 3–10 ohms resistance.
d. Person in contact with fitting and earth.
f', *d'*. Service transformer earth (*d'* or *f'* is optional, but *f'* is usual).
f. Possible earth-current flow, with or without one earth connection on the transformer.
e. Service transformer, without earth connection.
e'. No earth-current flow, hence no difference of potential.

Note.—Hazards are the most extreme where *one* earth connection is used, at the starting-point, such as at the distributing centre.[1] During a fault to earth the momentary rush of current may set up excessive voltages not possible where several earth connections are installed in parallel, the collective resistance in the latter case being low and much more dependable. There is also danger of excess potential rise between the distributing centre neutral earth and a person in contact with earth and touching the neutral wire of a house fitting.

In future overhead distribution practice it should not be an uncommon sight to see high-tension and low-tension conductors

[1] For some time past, the telegraph and telephone engineers of the U.S.A. have evinced special favour towards *multiple earthing* of electric power systems where earthing must be adopted. The Central Electricity Board has just commenced earthing at each substation—*this is directly against the Regulations,* but it is a highly commendable practice.

on the same pole line. Under normal operative conditions these two distinct circuits will exert practically a mutual influence over each other; the high-tension is, of course, the most active for producing abnormal conditions. If an insulator should crack, or an earth occur in any other way, causing a leakage current to flow, the high-tension circuit could induce a dangerous voltage on a "*dead*" low-tension circuit (see fig. 44). To overcome this danger to a large extent, the low-tension circuit should be operated with (or have) the neutral effectively earthed. However, the condition is not *completely overcome until the high-tension circuit neutral is also earthed* (see fig. 44), because of the possible pulsating arcing earth disturbance on the high-tension circuit, which will continue to induce a dangerous voltage on the low-tension (and on dwelling-house lighting installations if not earthed on each service) and thus endanger low-tension appliances, apparatus, etc.

One of the most serious secondary voltage dangers is due to arcing earths on the high-tension (primary) side. The voltage induced by arcing earths *on unearthed circuits or systems* may reach 3·5 times the normal phase to neutral voltage.

For a three-phase four-wire system with the neutral earthed and taken out to the distribution transformer, it may be good practice to install lightning arresters of reduced rating. If the neutral conductor is not earthed beyond the station or distributing centre, a risk of arrester failure is also involved because the line-to-earth potentials may become displaced at certain distribution points. Where the neutral point is earthed only at the station, lightning disturbances often occur on it at other points, so that transformers and other apparatus and appliances are endangered.

Theoretically, earthing the transformer case or tank should be effective as a means of protection from excess potential due to lightning discharge and also to potential difference arising between primary and secondary. Theory indicates that earthing transformer cases and tanks should be efficacious in protecting the transformer windings. Connecting a transformer case or tank direct to earth may make the protection from lightning independent of earth resistance, and may reduce the effect of the impedance of the earth wire between the arrester and earth; the transformer secondary earth-connection and the long secondary main to services is almost analogous to this.

Concerning overhead lines, which form part of transformer systems, there are, according to law, provisions "to prevent danger from a broken conductor by carrying a neutral or an earthed wire from pole to pole, and so to arrange the conductors in relation

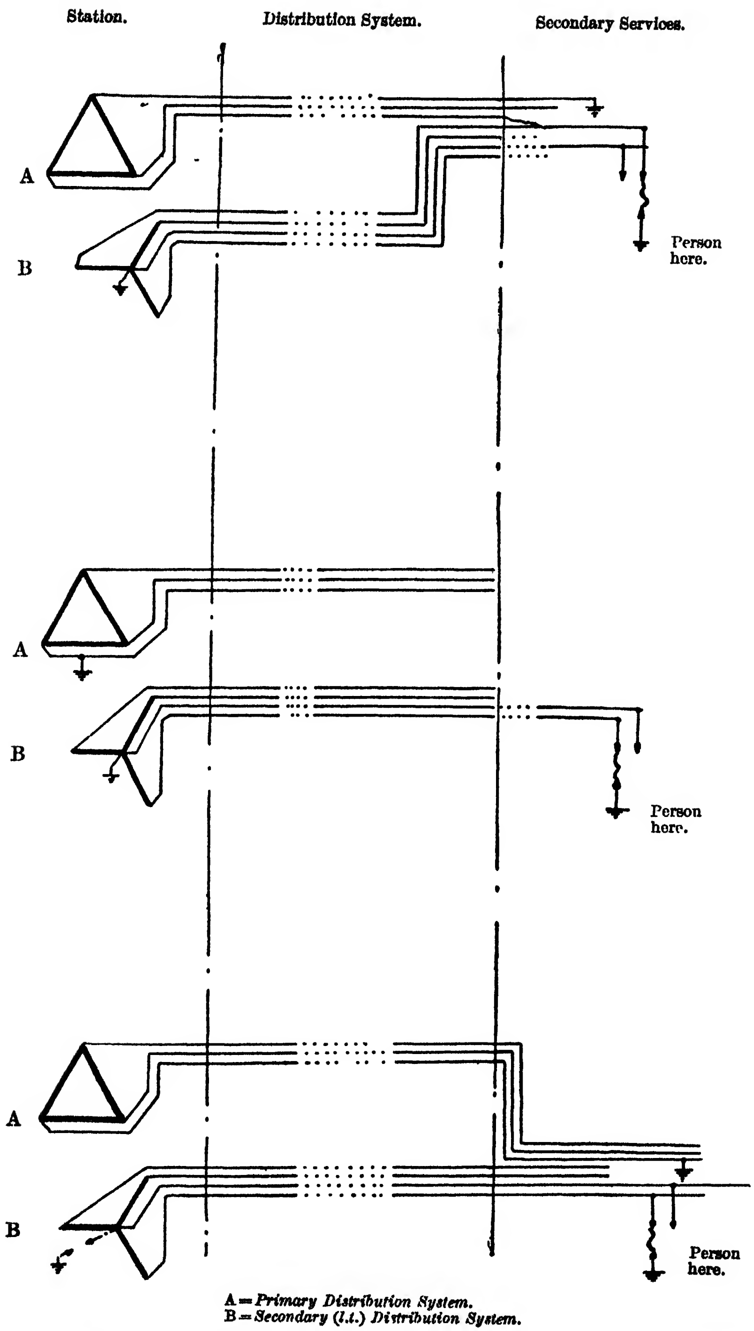


Fig. 44.—Showing Three Dangerous Probable Operating Conditions with Secondary Earthed at Station End Only.

with one another that in the event of breakage of any one of them the conductor shall make contact with the earth wire." (This safety method is obviously doubtful in practice.[1]) Also, "precautions shall be taken to prevent danger from leakage by connecting the metal work of all insulators to a continuous earth wire." (This cannot stop all danger from leakage.[1]) Also, "where a conductor crosses over or under, or is in proximity to, any other overhead wire, precautions shall be taken to prevent contact, due to breakage or otherwise, between the conductor and other wires." (Also a doubtful protection condition in practice.[1]) Also, "adequate means shall be provided to render any line-conductor dead in the event of it falling, due to breakage or otherwise. All metal work other than conductors shall be permanently and effectively connected to earth; for this purpose a continuous earth wire shall be provided and connected with earth at four points in every mile, or, alternatively, the metal work shall be connected to an effective earthing device at each individual pole." (This manner of *multiple earthing* leads us nearer to the protective practice desired. *i.e.* earthing the secondary neutral wire at each individual pole carrying lines feeding dwellings, or, better still, earthing all non-current-carrying metal work of electric installation on the premises. Surely, if it can be allowed on pole lines subjected to greater potentials and relatively heavier current multiple-earth discharges, and which usually have a much more *in*effective means of protection than a dwelling-house installation, it can be allowed in dwellings for the same reasons, quite independent of the more important requirements such as greater security of life and/or property.[1]) Moreover, "the design and construction of the system of earth connections shall be such that when contact is made between a line-conductor and metal connected with earth (through a person's body[1]) the resulting leakage current shall not be less than twice the leakage current required to operate the devices which make the line dead." (As a fraction of an ampère can kill, it is perfectly obvious that a *dangerous* current may be far too small to operate any device which will make the line dead, and *the* most positive security is multiple earthing.[1]) See also pages 178 and 193.

If a metallic neutral return circuit exists, exact calculations at any point can be made for any condition of current flow when the resistance at that point is known. Earthing at one end only (say at the supply end, which is the most effective end because voltage is best maintained there) may give rise to a far greater difference of potential to earth at the other end of the metallic circuit than

[1] The author's words and opinion.

in the case of an earth return circuit, which latter acts as a conductor possessing a gigantic cross-section, so that the current to earth can distribute itself over a very large area. In this respect it is of some practical interest to note that ten miles of 0·10 sq. in. copper conductor have a resistance exceeding 4 ohms at 20° C.; an aluminium conductor of the same size and length has a resistance very much higher, yet the earth resistance for the same length is often but a very small percentage of these values. Hence the impedance of the earth circuit may be relatively very small as compared with the looped conductor and its earth return—favouring copper and the earth return. Among other things, this points to the advantages of earthing at the consumer's terminals for safety of the consumer's apparatus, equipment, installation, property, the safety of his life and the lives of others.[1]

It is stated that[2]: "where an h.t. or e.h.t. supply is transformed for use at a lower pressure, or energy is transformed up to above low-pressure, suitable provision shall be made to guard against danger by means of the low-pressure system becoming accidentally charged above its normal pressure by leakage or contact from the higher-pressure system." This is laid down mainly with the idea of reducing to a minimum the possible danger to persons should they make contact accidentally with any live "*low-pressure*" conductor, and also with the idea of eliminating the possibility of an arcing fault to earth causing a fire, as well as ensuring a more rapid and positive disconnection of the faulty circuit. The questions so far brought out in this chapter fully endorse this Rule, but they are at issue because the Rule does not complete the requirements and neither accomplishes nor practises what it is truly intended and expected (by the public) to do.

The foregoing discussion has had for its chief object the purpose of protecting persons from excess voltage over and above the normal supply voltage of 230 volts to earth. Briefly, it can be taken as a general rule that the more remote a high-tension conductor or current is from a low-tension service, the farther away can the permanent earth connèction from the low-tension service be, and *vice versa*. Careful following along these lines of thought will decide as to safety for the public ih so far as the impressed or/and induced voltage (down to the present standard of 230 volts to earth) is concerned. Below 230 volts we have but two positive

[1] See *Journal of Institute of Electrical Engineers*, vol. lxvii, June 1929, p. 735, stating: "*Multiple* earthing will help us enormously in some of the country districts when we want to operate transformers in parallel."

[2] See H.O.E. Regulation No. 20.

and safe methods, namely: (1) put in the proper wiring installation referred to hereafter, and (2) earth at the service.

It is obvious that we can obtain, for an uncertain period, an approximately equivalent protection by earthing every metal (non-current-carrying part) fitting and appliance for every outlet in every electric installation; but why attempt this uncertain and unreliable practice (perhaps concerned with a matter of life and death) when only one positively reliable and effective earth per complete house-installation will suffice? Moreover, why have more than one insulated conductor per dwelling? Also, why have more than one terminal or pole or contact per fitting, etc.? Each *independently* earthed plug, switch, lamp-holder, flat-iron, etc., may have a much more variable (and certainly a less perfect zero) earth potential than when using one general permanent earth-connection, suggested hereafter. In the one case the earth is permanent, while in the other case it is accidental, which latter can be classed as a decidedly dubious condition. Also, do we practise engineering and make laws for safety to life that depend on any and every person or person's will, whim, feeling, and action? Why depend on all these variables to keep intact for all time the earth connection on each and every fitting, etc. throughout the whole Kingdom, when we can positively and permanently and completely wipe out the hazard to life by making the earth connection to the exposed non-current-carrying parts of each and every fitting, conduit, etc. at one point per dwelling? When independently connected to earth, why expect every plug, lamp-holder, kitchen-stove, boiler, flat-iron, etc. to be always positively earthed and always give a faultless, fool-proof, safety-from-shock installation, knowing perfectly well that the conditions depend upon so many unknown and uncontrollable variables, capable of changing at any moment, and making an uncertain and decidedly dangerous practice as compared with the one positive earthing method for fittings and metal conduit, etc., recommended here?

It is true that there are diverse opinions about earthing the neutral on the premises, or at the first pole or first available underground connection; nevertheless, if we desire security for the public against shock or death from 230 volts to earth, we should operate a system of wiring and installation that incorporates all exposed metal and dangerous non-current-carrying parts as a part of the actual wiring installation, thus avoiding loose connections and wires and flexibles; that is to say, we should install a wiring system that can, as desired, positively earth all the said metal parts at one operation. The principal difference of opinion that

will arise is: (1) Shall the earth form a part of the electric circuit, and thus have each dwelling-house wiring-installation protection help other dwelling-house wiring-installation protections in case of faulty protection in one or more? or (2) Shall we depend for protection on the one general earth connection for all metal parts per dwelling-house wiring-installation, independent of the electric circuit?

Several different conditions exist, none of which favour the present practice of independently earthing the non-current-carrying metal parts of fixtures and appliances for positively securing safety against shock, etc. Some of the conditions are:

(*a*) With or without a general or independent earth connection, it is possible to receive 230 volts to earth from the insulated wire.

(*b*) With one general earth connection per dwelling-house installation, using one or two insulated wires, and one or two terminals per switch, plug, etc., it is *impossible* at any time to get a shock by touching any metal part of the lamp-holder, plug, conduit, etc., because it is fixed at earth potential [see fig. 45 (A)].

(*c*) With independent earth connection on each switch, plug, lamp-holder, flat-iron, etc., using two or three insulated wires and two or three terminals (note that one insulated wire and one terminal cannot be used) per switch, plug, etc., there is always the risk of receiving a dangerous shock when touching any metal part of the said switch, plug, etc., which is *not fixed* at earth potential [see fig 45 (B)].

(*d*) For (*b*), if the metal part of any electrical fitting or appliance accidentally makes contact with the one (there need be only one) insulated conductor, the voltage is positively and instantaneously cut off, due to short-circuit; hence, no danger from shock [see fig. 45 (A)].

(*e*) For (*c*), if the metal part of any electrical fitting or appliance accidentally makes contact with any one of the two insulated conductors, the voltage may not be cut off and the danger of shock is present or is possible [see fig. 45 (B)].

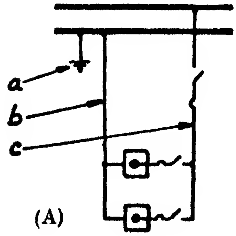
Fig. 45, (A) and (B), gives a clearer idea of conditions associated with exposed metal parts of fittings, conduit, etc., when connected to, or made part of, the earthed return of the circuit.

As one remedy we can, of course, install 400/115-volt supply; this offers a more efficient lighting system, and it also offers a safe voltage of 58 volts a.c. to earth; but why have thousands of small transformers scattered about, and why return to the practice we

discarded a quarter of a century ago? Here are the three main reasons *why*:

(1) The standard voltage to earth (230 volts a.c.) is considered to be too dangerous.

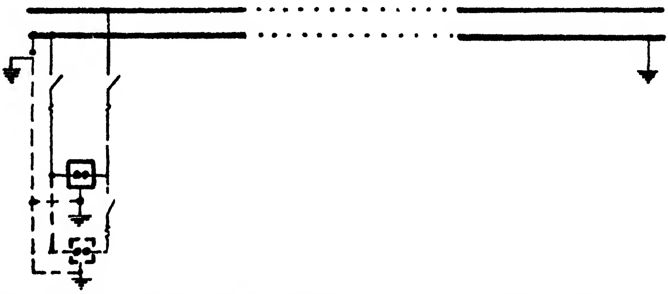
FIG. 45.—Showing clearly that, to obtain the desired *Safety of the Public*, Multiple Earthing must be practised, *i.e.* one general earth per dwelling employed.



(A)

a—Service earth-connection (*water main*, etc.).
b=*Earthed* side of installation (metal conduit, wire, *or both*).
c=*Insulated* side of installation, which is always connected to the insulated terminal of lamp-holder, socket, appliance, etc.

Note.—The least number and amount of wires, etc., is used, and non-current-carrying parts are earthed in the most effective manner and form part of the return circuit; hence all materials installed are most effectively employed *for maximum service and safety.*



(B)

(A) Safer because the insulation area and surface is greater for equal size of fitting (lamp-holder, plug, etc.); but, *under abnormal conditions*, two terminals will be safer than one.
More economical because requiring only one insulated wire, one single-pole switch, one single-pole fuse-block and less insulators, because the metal conduit and fittings form the return.
More reliable and giving greater safety from shock because all metal non-current-carrying parts are positively and effectively earthed on the premises and form part of the system of wiring.

(B) Safety much less because the insulation area and surface is very much less (see figure) for equal size of fitting (lamp-holder, plug, etc.).
More expensive because two (perhaps three) insulated wires, one double-pole switch and fuse-block, more insulators, etc., are required, with or without the service earth connection.
Much less reliable and not safe from shock because there is no knowing how long the one and only earth connection will remain intact; the earth connection for the neutral is too far remote and is subject to open-circuit, also to short-circuit with high-tension wires, etc. For greater safety we may install and independently earth the third conductor as shown in broken line, or we may directly earth the service, which is generally a more reliable procedure and amounts to the same thing, as will be seen, distinct from the relatively inferior quality of the independent earth connections made.

(It will be noted on close examination of (A) and (B) that multiple earths are used in each case, but (B) is the more costly, less reliable, and probably the more dangerous method of the two when earthed at the service, and decidedly dangerous when non-earthed at the service.)

(2) We do not wish to earth the electric circuit at the premises.

(3) We do not have the proper wiring installation and system.

By independently earthing the metal parts of fittings and appliances there is no certainty as to how long an earth connection

will remain intact; this also applies to earthing at the supply end *only*. It is also unnecessary to shroud switches, plugs, etc. in insulating material; this is poor practice and it does not safeguard the public against all the possible dangers, nor is it permanent. It will not stop the 230-volt to earth risk of an exposed wire, say a frayed flexible cord of a flat-iron or other appliance, being accidentally handled and contact made through the body to a damp concrete (kitchen or bathroom) floor or to metal work, such as a lined sink.[1]

From the case quoted in the footnote we see that, in the first place the current fault was not sufficient to blow the fuse yet sufficient to "freeze" and overpower the woman; in the second place it is seen that we may have a condition of faulty installation practically beyond our control, assuming the flexible cord and not the lamp-socket or holder or any metal part is at fault; generally the fault is with the latter, and is therefore controllable when the proper wiring installation is made. For a faulty lamp-holder or other metal part, under condition (A) of fig. 45, there should be little reason for the slightest shock.

Why deceive ourselves that a 230 a.c. secondary voltage to earth is quite safe without multiple earths; that there is no necessity to earth at the transformer or substation *and* on each service; that sufficient safety can be given to the public without earthing on each service; that we must not use secondary multiple earths?

Also, in this connection, who can say there are no *star*-connected three-phase motors or apparatus in any of the industries throughout the Kingdom with the neutral point connected to the earth or the earthed frame? Again, who can say there are no non-current-carrying metal parts of electric fittings and appliances, installed in dwellings throughout the Kingdom, connected to earth at the respective dwelling and conforming to fig. 45 (B)? It is recognised that where these exist they are a violation of the Regulations.

The dwelling-house (or domestic) installation is the more important of the two cases, because of the vastly greater number of persons exposed to the life hazard. Comparing (A) of fig. 45 with (B), it is seen that there is no necessity to have more than one terminal per switch, plug, lamp, etc.; that vastly greater insulation

[1] *The Electrical Review*, p. 616, 5th April 1929, quotes "the death of a woman who received a fatal shock. . . . The woman had been standing on a zinc-covered sink in a scullery, and an electric lamp swinging from the ceiling was knocked against her. . . . When found, the woman had her arms around the lamp cord. The electricity supply was cut off . . . the woman was found to be dead. . . . A formal verdict was returned." (Glasgow report.)

is obtained for the insulated terminal of lamps, plugs, etc.; that a third conductor is saved, and other savings also effected; that the wiring method shown in (A) offers *the* truly effective security as far as it is possible to attain this, and does so at the lowest cost and with the maximum of reliability; that *without the earth connection* at each dwelling, the service is ever subjected to the following life hazards:

(*a*) The possibility of a dangerous potential rise above earth between the transformer earth connection and the service accidental earth.

(*b*) The possibility of a high-tension cross with service leads.

(*c*) The possibility of impressed and/or induced excess dangerous voltage on the secondary mains.

(*d*) The possibility of the transformer or substation earth connection (which is the *only* earth) becoming open-circuited.

(*e*) The possibility of high-tension and low-tension conductor crosses and/or high-tension (primary) earth and/or breakdown of transformer insulation on secondary, any one of these *three* becoming positively dangerous to both secondary mains and services alike.

With the *earth connection at each dwelling, not one* of the above-mentioned dangers to life and property [from (*a*) to (*e*) inclusive] is possible. Hence, multiple earthing [preferably with the adoption of the simplified wiring method shown in (A) of fig. 45] is the only means of giving absolutely reliable permanent and almost faultless security to life and property.

Whether or not we connect the metal parts of fittings and conduit direct to the dwelling-house earthed neutral is neither here nor there, as by earthing the metal non-current-carrying part of fittings and appliances we indirectly connect them to the same earthed circuit. By this indirect practice, however, we make matters worse, and this at the expense of installing an extra insulated conductor involving insulators and other materials and labour. What is done in (A) of fig. 45 is to bring one side of the dwelling-house circuit and the metal parts of fittings and conduit to earth potential *in one operation*; whereas, in (B) of fig. 45, the same thing is not accomplished by using an extra insulated conductor, extra materials and labour, etc. This latter method is the ordinary present-day universal house-wiring practice; it increases all items of cost, and it is a danger (as already shown) where a secondary

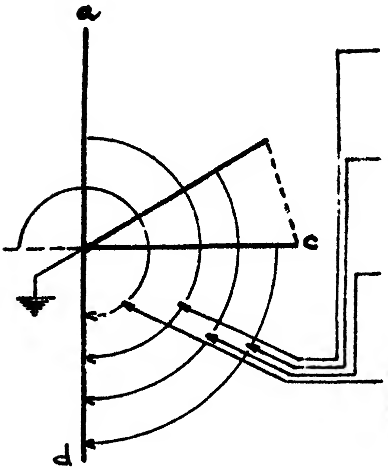
a.c. voltage of 230 volts to earth *is isolated* from earth on each service.

This vital and important national question of multiple earthing is discussed here because we are about to experience changes from underground to overhead practice, which changes require certain modifications in the Regulations to provide for the increased hazards, changes in the present-day habit of thinking in terms of underground practice, and closer co-ordination of the power and communication systems. Moreover, there are those bent on having engineers, and the public in general, believe that earthing at any other point than the supply end is a fallacy to be condemned absolutely; they say:[1] "it is neither good advice nor common sense that we are given . . . where it is stated that we may earth the neutral at the supply end and at other convenient points"; they then qualify these remarks by saying:[1] "it is fortunate for the public that the Electricity Commissioners have legal sanction"—etc.; and:[1] "the rules of the Electricity Commissioners have indeed been formulated none too soon." Needless to say, the time is not far distant when the public should (and will) demand an exacting lesson for and from this class of "adviser." The hazards and dangers are not mythical; they are decidedly apparent and real, and he who advises to the contrary may most likely be the first to be directly subjected to some of the hazards he claims as non-existent. It is not the poor innocent that should suffer; but he who should know better and is paid to know better and do better should guard his fellow-men and apply that practice of safety herein (and once again) recommended for this country.

Moreover, why not endeavour to create and maintain lower general costs to those paying for their needs? That is to say, directly due to the adoption of the *high* lamp voltage of 230 volts, the supply authorities claim lower initial line-copper costs and lower circuit-operating losses *on load*, but, the hundreds of thousands of consumers are, in consequence, subjected to higher cost for installation, higher cost of lamps, together with more frequent burn-outs, due to shorter life of the lamps, greater energy consumption per gas-filled lamp, and greater danger to life due to the higher voltage, etc. The great drain on public monies, which is a continuous drain during the life of the system and supply, should be obvious to all those technically trained and chosen and paid by (for serving properly) the general public.

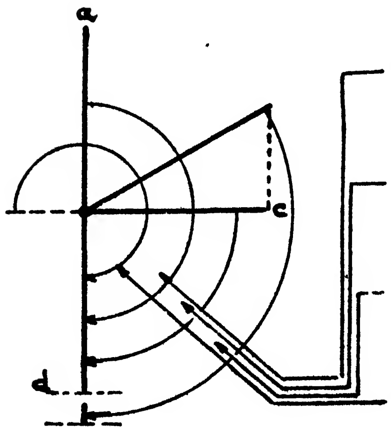
[1] See *Engineering*, p. 243, 22nd February 1929.

FIG. 45a.—SHOWING TRUE COMPARISON, WITH THE DIRECT CURRENT SYSTEM, FOR MAXIMUM VOLTAGE ABOVE EARTH AND FOR MAXIMUM VOLTAGE BETWEEN CONDUCTORS.



System.	For the same Maximum Voltage above Earth, and taking E=100 Volts between any Conductor and Earth. (*Relative voltage danger*). *Maximum Voltage between Conductors=*
Single-phase	$2E\sqrt{2}=283$
Two-phase 3-wire .	$\sqrt{2}E\sqrt{2}=200$
Three-phase	$\sqrt{3}E\sqrt{2}=245$
Two-phase .	$2E\sqrt{2}=283$

ad=single-phase=one phase of the two-phase system, or two legs of a *quarter*-phase system.



System.	For the same Maximum Voltage between Conductors—*Relative Amount of Copper Required.*
Single-phase	100% ; that is, $2/\cos^2\phi$
Two-phase 3-wire .	145% ; ,, $2{\cdot}92/\cos^2\phi$
Three-phase	75% ; ,, $1{\cdot}5/\cos^2\phi$
Two-phase .	100% ; ,, $2/\cos^2\phi$

Note.—These voltage and phase diagrams are drawn to scale for the purpose of visualising the true relations.

CHAPTER IX.

PHASE TRANSFORMATION.

THEORETICALLY, there are many different ways of converting three-phase to two-phase and other phase relations and making other transformations.

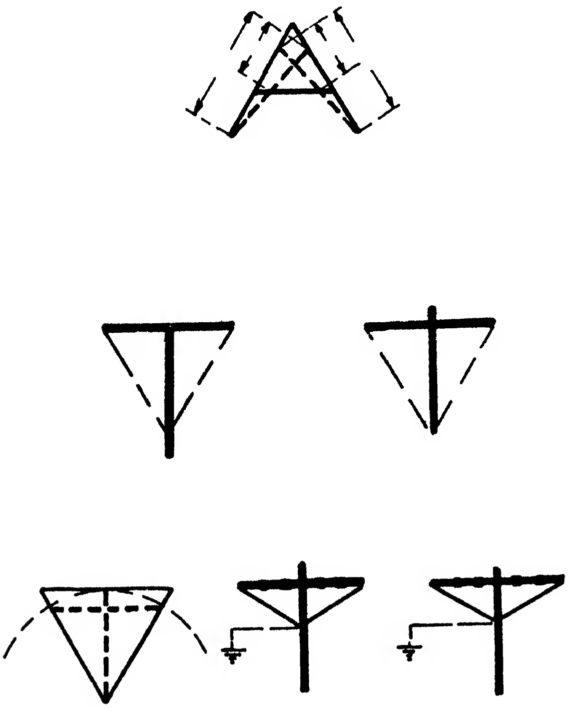
From the operating engineer's standpoint, a few per cent. saving in initial first cost is hardly worth considering when compared with the equivalent operating advantages such as flexibility, adaptability and reliability under service conditions for the various standard systems.

The best known and perhaps the oldest method for transforming from three-phase to two-phase, or *vice versa*, is the system known as the "*T*" (inaccurately called the Scott connection, which later was covered by patent for a three- to two-phase system, also representing the "*T*" connection). It is, however, not generally known that this method of transformation and connection does not derive its popularity from specially outstanding advantages. The "*T*" connection, whether for three-phase to two-phase or for three-phase to three-phase, is, as already mentioned, an emergency method differing in practice only very slightly from the well-known emergency "*V*" or open-*delta* connection.

For three-phase to two-phase, or *vice versa*, there are transformation methods quite easily effected by a single three-limbed iron core and giving advantages in economy and/or greater flexibility and/or reliability and/or adaptability, practically equal to the "*T*" or Scott connection. Furthermore, it may be said that, for equal transformer and service reliability, service conditions for the various standard systems of distribution and/or transmission, as well as for equal cost at equal total efficiency, the "*T*" or Scott connection does not possess special advantages.

For the ordinary "*T*" or Scott connection, which is the system requiring the minimum of two single-phase transformers or two two-limbed iron cores (making four iron cores in all), the windings on one side (on the primary or the secondary as the case may be) of the two transformers are connected in the form of a "*T*," as

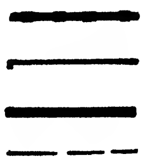
shown in fig. 46 (*b*), and the two ends of each transformer winding (on the secondary or the primary as the case may be) are left free for two-phase four-wire service; or, the two windings may be con-



(*a*) "*A*" system. Showing method of obtaining two different two-phase voltages with or without neutral, using one polyphase unit *only*.

(*b*) "*T*" or Scott system. Only single-phase units can be employed, requiring *four* to *six* iron cores in all, as against *three* iron cores for (*a*).

(*c*) Using one polyphase unit in each case, requiring *three* iron cores in all.



Represents resultant two-phase voltages.

" three-phase windings.

" two-phase windings.

" three-phase resultant voltages.

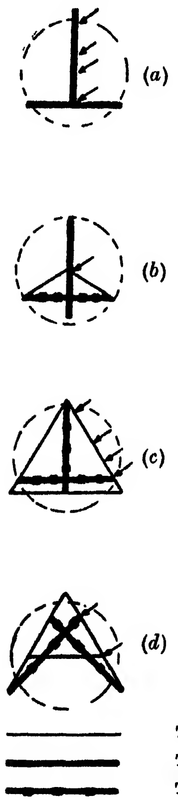
FIG. 46.—Showing Four of the Best Methods of Transformation from Three-phase to Two-phase or *vice-versa.*

nected together on the three-phase side at the point where the intersection occurs [see fig. 46 (*b*) (right)] instead of connecting at the end of the commonly called "86·6 per cent. winding."

As there are no two-phase transformers for the "*T*" or any other two-phase method, and as a single three-limbed iron core transformer (making three iron cores in all) can be used to give at least as great a reliability and as flexible a service for the same

system, shown in fig. 46 (*b*), the relative first cost for equal efficiency is, in actual practice, no better than with the methods of fig. 46 (*a*) and (*c*), which give *five* different methods [two for (*a*) and three for (*c*)], or, more truly, three distinct connections, one from the "*A*" system, one from the *delta* system, and one from the "*Y*" system.

Fig. 47.—Showing Relative Number of Taps required per Unit (for Single-phase Units) for Equal Flexibility.



Three-phase windings.
Two-phase windings.
Two-phase resultant voltages.

A spare unit is not required for (*c*); a spare unit can always be used with advantage for (*d*) whether for normal operation or in the case of a faulty transformer.

If the two single-phase "*T*" or Scott-connected transformers are made interchangeable, to compare with fig. 46 (*c*) using a three-limbed iron core, 15·5 per cent. greater kVA capacity than that of the load is required, just the same as when operating in "*V*" or open-*delta*. Also, it is usual to have the corresponding halves of *both* high-tension and low-tension windings interlaced for equivalent interchangeability. Furthermore, with this connection, third-harmonic pressures and currents are present to some extent, and especially so for equal voltages to earth.

Over twenty-two years ago [1] the author adopted the three methods shown in the three figures of fig. 46 (*c*) for supplying a combined three-phase four-wire and two-phase four-wire secondary distribution in a large city having two competing electricity undertakings, one with three-phase four-wire distribution and the other operating a two-phase four-wire system, both by means of overhead lines. A patent was granted to the author in 1907 for the system shown in the left-hand diagram of fig. 46 (*c*). Patent proceedings for the other two methods of fig. 46 (*c*) were dropped at the time, chiefly because difficulties were put in the way, and the expense and trouble was not considered worth while.

In fig. 47 are shown the four methods referred to above, based on equal phase voltages for the two-phase side. Methods (*b*) and (*d*) show the least number of taps for equal flexibility, the arrowheads indicating the number of taps required per phase for equal

[1] *Distribution of Electricity by Overhead Lines* (Griffin), p. 8.

interchangeability; for instance, (*d*) shows four taps in all as against eight for (*a*), and (*b*) would usually have no less than (*d*).

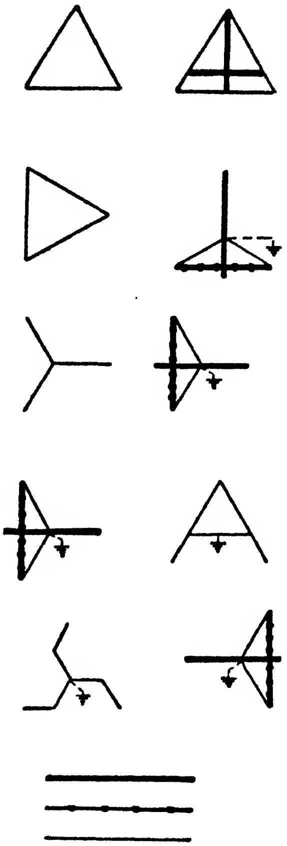
The *delta* connection is known to be desirable and economical for secondary voltages and heavy currents, and the two-phase system is invariably a secondary system of distribution. Although no neutral point is available for the *delta* connection, large unbalance loads can be supplied, as such loads only produce unbalanced voltages proportional to the internal impedances of the windings connected in *delta*; this inherent advantage also favours the "*A*" system, which has a relatively smaller *delta* winding as compared with the *delta* system for equal phase voltage.

For maximum flexibility, adaptability, reliability and safety, either the secondary or primary winding (as the case may be) should be tapped so that the points are made available for various operating methods such as shown in figs. 48 and 49, which latter shows the emergency methods for operation when a phase unit fails.

For normal (or abnormal) operation of the "*A*" system shown in fig. 49 (*c*), where the small winding can be used or retained to keep the *delta* closed, adaptability and flexibility are attained. The system is suitable to three-phase three-wire and/or four-wire, or/and two-phase three- or four-wire, secondary distribution. It offers reliability, safety, and flexibility, in that it is possible to supply satisfactory polyphase (three-phase and two-phase) service when one phase-unit is faulty. With the completed "*A*" system of fig. 49 (*b*) and (*c*), combined three-phase, two-phase, and single-phase service can be given; the third-harmonic current will not be delivered to the line but will circulate in the *delta* thus provided by the "*A*" connection; satisfactory three-phase four-wire as well as two-phase four-wire service can be given at the same time, and, for the methods of fig. 49 (*b*) and (*c*) there will be lower voltages to earth for equal phase voltage than with either the "*T*" or Scott method. Moreover, as a spare unit is usually available on most distribution systems, it can be used to the best advantage (and still be considered as a spare) by connecting it in the circuit of fig. 49 (*b*) or (*c*), thus making one or the other of these two methods both flexible and adaptable for normal and abnormal operating conditions, much more so than in the case of the "*T*" or the Scott connection. For two single-phase units, and using the open-*delta* connection, the same two-phase voltage is obtained as for fig. 49 (*c*), and this is high compared with the "*T*" or Scott connection.

Fig. 50 (1) shows a method of obtaining three-phase and two-phase service from the "*A*" system, using one three-phase unit.

Fig. 49 (*b*) and (*c*), and fig. 50 (3), also show various methods for obtaining three-phase and two-phase from the "*A*" system. The connections of fig. 50 (2) show a two-phase four-wire system and a quarter-phase four-wire system converted from the "*A*" system shown in fig. 13. One of the chief advantages is to retain the



Connections same as in (*c*) of fig. 47.

(*a*) Connections for three-phase four-wire and two-phase five-wire.

(*b*) Same as (*a*), but with *star*-connected primary.

(*c*) Connections for converting three-phase four-wire or/and two-phase four- or five-wire primary to three-phase "*A*" system providing a four-wire combined light and power service.

(*d*) Connections for converting interconnected-*star* (*zigzag* or "*Z*") primary to three-phase four-wire or/and two-phase four- or/and five-wire.

Winding for two-phase and part three-phase.

Transformer windings.

Two-phase resultants.

FIG. 48.—Showing *Delta, Star, Zigzag,* and "*A*" Connections for Three-phase to Two-phase Transformations.

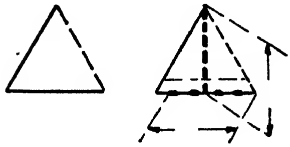
delta; in other words, retain the "*A*" connection for the different system and operating requirements, whether under normal or abnormal conditions.

At the present time a stage of electrical development has been reached when it is safe to say that several of the *main* disadvantages of the two-phase systems are:

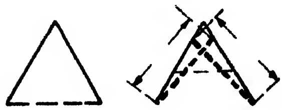
(1) With general standardisation of three-phase motors and apparatus, the equivalent two-phase must with time be

more and more difficult to obtain, because manufacturers cannot commercially afford to make and keep in stock, or take any interest in, say, one or even a dozen undertakings, when there is a world of three-phase motors and apparatus to think of and supply.

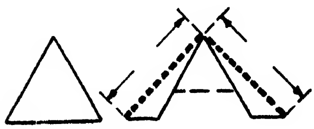
(2) The two-phase motor and transformer equivalent is



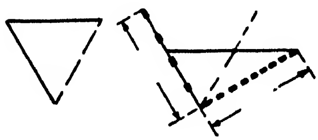
(*a*) Three-phase to two-phase; same as fig. 47 (*c*) but with one phase-winding less.



(*b*) Three-phase to two-phase; same as fig. 47 (*d*) but with one phase-winding less.



(*c*) Three-phase to two-phase, with the small phase-winding divided into two equal parts and connected as shown. Same as one-half of fig. 50 (2).



(*d*) Three-phase to two-phase with one phase-winding omitted, and "*A*" or *delta* three-phase connection made as shown, which provides a high two-phase voltage such as with the Scott connection using two windings.

FIG. 49.—Showing Three-phase to Two-phase Operation with One Phase-winding Disabled, *i.e.* operating in each case with two single-phase transformers (except in case (*c*) for "*A*" system conversion).

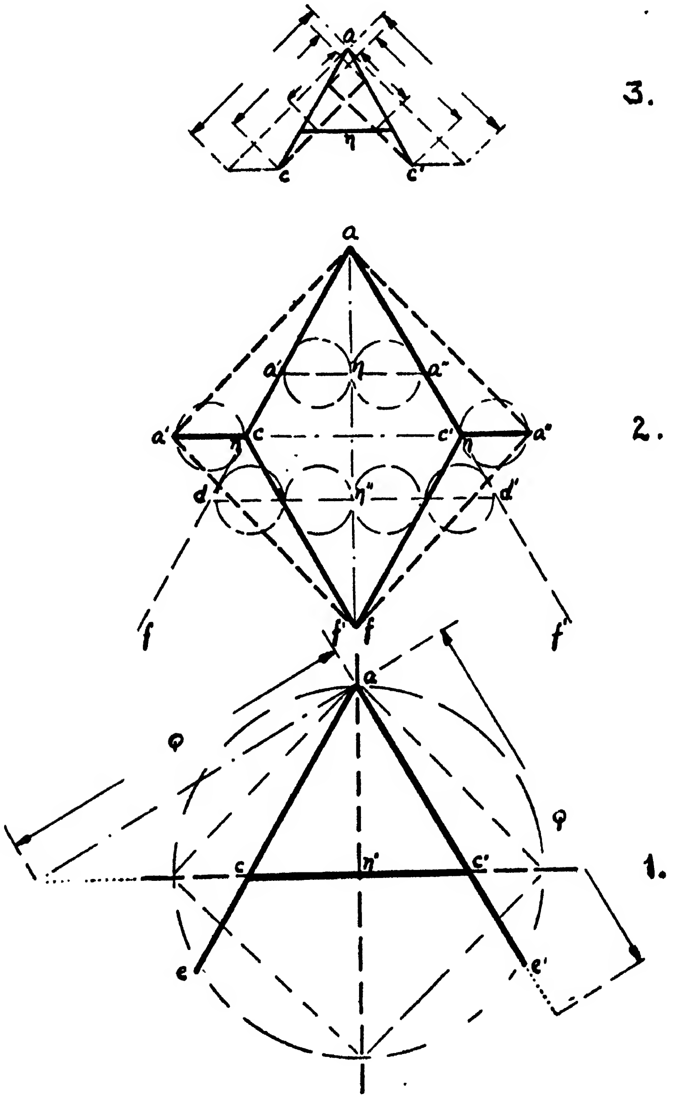
relatively more expensive to manufacture, and its cost is likely to increase because of the new three-phase conditions created.

(3) There is a bigger loss of kVA capacity in transformation and in the connections and the types of units used.

(4) The two-phase system cannot make use of polyphase transformers, and therefore cannot enjoy all their advantages.

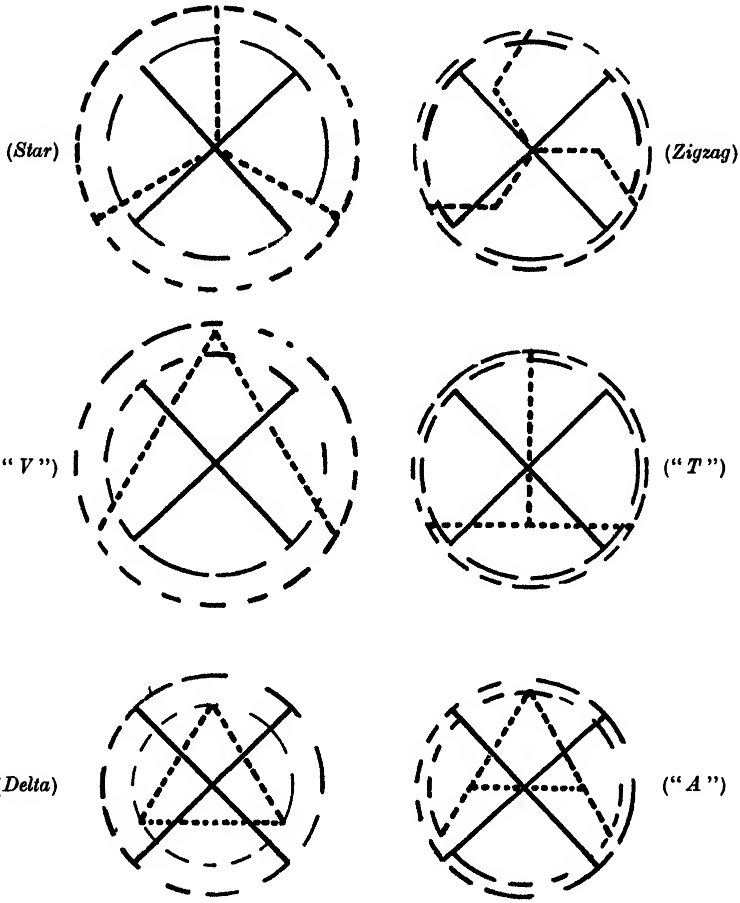
(5) The relative efficiency of two-phase motors and other two-phase or equivalent apparatus is less.

FIG. 50.—Showing: (1) Method of Converting the Two-phase Four-wire System to Three-phase "*A*" System; (2) Method of Converting the "*A*" System into a Two-phase Four-wire System or/and a Quarter-phase (or system with four two-phase relations) Four-wire System; (3) Method of Obtaining Two-phase Directly from the "*A*" System.[1]



[1] *Methods Patented.* For the two-phase system QQ of fig. 50 (1) only two single-phase units may be used, just the same as for the "*T*" and "*V*" systems (see also fig. 49 (*d*), showing use of two units only).

Fig. 51.—Showing Approximate Relations of Transformer Winding Required for the Different Systems (*Star, Zigzag,* "*V*," "*T*," "*A*," and *Delta*) Based on Equivalent Total Value Required for the Two-phase Four-wire System (*not relative total* kVA *capacity*).



Note.—The kVA capacities of the "*V*" and "*T*," respectively, are reduced by 15·5 per cent., and this amount can be partly added to the "*A*" system because the whole is effective.

For the three-phase systems there are advantages in using three-limbed core units as compared with two or three two-limbed units, which latter are the only available types for the two-phase system.

(See Table VI. for relative total rating of the *star, delta,* "*V*," "*T*," and *zigzag* systems.)

(6) If an earthed neutral is used, there is a greater risk of system disturbance, short-circuit, etc., due to the greater number of conductors per main or power circuit.

(7) If the neutral is earthed, danger to life is greater if the phase-to-phase voltage is higher. If the voltage is the same as with the three-phase system there will be greater expense in line-conductor for the circuits, etc.

(8) If the neutral is isolated, the secondary system can well be classed as a great life hazard.

(9) If the lighting system voltage is not standard, the total cost for lamps will be greatly increased.

(10) For motive power, the consumer subjected to meter charge will always be the greatest loser as compared with the user of the same power delivered to the shaft of an equivalently rated three-phase motor or service.

(10*a*) For lighting, these conditions may be no better, due to the possibility of using non-standard lamp voltage.

(11) With the progress of standardisation, two-phase plant will become more and more rare and obsolete.

(12) Because of the trend of practice, future development of any two-phase system can be carried on only at relatively greater expense to the public *in particular* as compared with the three-phase system.

(13) Switchgear, wiring, etc. are more complicated and more expensive than with the three-phase system.

(14) For an equivalent motor service the two-phase system requires *two* two-limbed iron core transformers (four iron cores) as compared with only one three-limbed iron core unit for the three-phase system.

(15) Power factors are less and third-harmonic pressures are higher for the two-phase system.

(16) Control equipment is more expensive.

(17) The relative power carried per conductor is smaller for equal voltage in the case of the two-phase five-wire system, which two-phase system is considered to be the most economical of all the different two-phase or quarter-phase systems.

In view of the afore-mentioned disadvantages compared with the National Electricity Scheme and general unification for this country, it would constitute a serious offence against all the public concerned if a two-phase or quarter-phase (occasionally called four-phase) system were allowed to furnish electrical light and power supply.

TABLE XVII.

RELATIVE OHMIC RESISTANCE AND TOTAL WEIGHT OF CONDUCTORS FOR DIFFERENT SYSTEMS.

System.	Equal Voltage to Neutral, Same Power Transmitted, Same Percentage Power Loss:							
	1	2	3	4	5	6	7	8
Single-phase two-wire .	E	2E	P/2E	$2E^2P$	1·00	1·00	2·0	1·00
Two-phase four-wire .	E	2E	P/2E	$4E^2P$	2·00	0·50	4·0	1·00
Three-phase three-wire	E	$\sqrt{3}E$	P/3E	$3E^2P$	1·50	0·667	3·0	1·00
„ four-wire	E	$\sqrt{3}E$	P/3E	$3E^2P$	1·50	0·667	3·0	1·33
System.	**Equal Voltage between Outer Conductors, Same Power Transmitted, Same Percentage Power Loss:**							
Single-phase two-wire .	E	2E	P(2E)	$2E^2P$	1·00	1·00	2·0	1·00
Two-phase four-wire .	E	2E	P(4E)	$4E^2P$	2·00	0·50	4·0	1·00
Three-phase three-wire	$2E/\sqrt{3}$	2E	$P/(2\sqrt{3}E)$	$4E^2P$	2·00	0·50	3·0	0·75
„ four-wire	$2E/\sqrt{3}$	2E	$P/(2\sqrt{3}E)$	$4E^2P$	2·00	0·50	4·0	1·00
„ four-wire *	2E	$2\sqrt{3}E$	P/6E	$12E^2P$	6·00	0·167	4·0	0·33

* The voltage to neutral in this case is $2\sqrt{3}E$.

Where

1 = Voltage to neutral.
2 = Voltage between phase- or line-conductors.
3 = Line current.
4 = Ratio of resistance per conductor to percentage power loss.
5 = Ratio of resistance of outside or phase-conductor to the single-phase resistance.
6 = Ratio of weight of outside or phase-conductor to weight of single-phase conductors.
7 = Number of outer or phase-conductors.
8 = Ratio of total weight of conductors to total weight of single-phase conductors.

Note.—In a single-phase system the drop in voltage would be twice the drop in one outer (main) conductor. In a three-phase three-wire circuit the drop in voltage would be 1·732 times the drop in one outer (main) conductor. In a three-phase four-wire circuit with a balanced load the drop in voltage would be the drop in one outer (main) conductor only. Since the number of conductors for these three systems are two, three, and four respectively, the amounts of copper required under the three conditions would be in the ratio of 2 : 3 : 4 ; but the amounts of power that could be transmitted would be in the ratio of 2 : 4 : 12, as shown in the above table.

CHAPTER X.

MODERN LINES FOR TRANSFORMER SYSTEMS.

As previously explained, about 90 per cent. of the troubles which reach and endanger a transformer come from the line side of the system. This means that present-day line design, construction, and maintenance are unsatisfactory and unreliable, and steps should be taken to cancel out the greater part of these troubles by installing a design and construction aiming at much greater reliability even if the initial cost be higher.

The most correctly-designed and best-constructed apparatus, line or system, is rarely the cheapest initially, but usually is the cheapest in the long run. In the case of the line, like the transformer itself, it is not the first cost that should always decide, but the annual costs with the resultant increased price for energy as well as shorter life and relatively less reliability. The best apparatus or line is that which delivers power in the most reliable and satisfactory manner and at the lowest cost. If we desire to decrease the 90 per cent. of troubles referred to above, good engineering requires that it be done with a general view of economy. That is to say, for a line or a transformer, if we can obtain a longer life with minimum cost of maintenance and minimum number of troubles (uninterrupted service), then we are justified in favourably considering a reasonable increase in first cost.

Throughout the foregoing we have seen that line and transformer always go together; one is dependent upon the other for service, but the former is always more susceptible to troubles than the latter, which is the reflecting point of all troubles. In view of this, and the ever-increasing importance of reliability, the desire is to design and construct safer and better lines. In this country the climatic conditions in particular, also the atmospheric conditions, are very hard on wood and steel constructions. During the greater part of the year the under-surface cells of the wood are more or less saturated with moisture, and not long after a badly treated wood pole is set into the ground it begins to rot just below the level of the ground. This rot and weakening means a considerable

diminution in security against breakage, inasmuch as the moment of resistance (M) is proportional to the third power of the diameter. Under the badly treated wood layer of between ½ and 1 in. depth lies the unimpregnated wood-heart; the poorly treated part becomes rotted or weakened and can be considered as non-treated raw timber, and the coefficient of the moment of resistance should no longer be taken as 7800 lb./sq. in. At its best, not allowing for the diminishing factor of safety, the decrease in bending moment for a 10-in. diameter pole at the ground-line, is shown by:

New pole . .	$10^3 \times 63{\cdot}8$	$=63{,}800$ lb.-ft.
0·5-in. rot . .	$9{\cdot}5^3 \times 63{\cdot}8$	$=54{,}700$,,
0·75 ,, . .	$9{\cdot}25^3 \times 63{\cdot}8$	$=50{,}400$,,
1·0 ,, .	$9{\cdot}0^3 \times 63{\cdot}8$	$=46{,}500$,,
1·5 ,, . .	$8{\cdot}5^3 \times 63{\cdot}8$	$=39{,}100$,,

Thus we have nearly a 40 per cent. decrease in load strength due to a rot of only 15 per cent. of the diameter.

Troubles from flashovers on lines equipped with earth (ground) wires are always more likely to develop at the poles or structures, where the value of the earth resistance is relatively high. Where the continuous earthed wire (or wires) is *insulated* from the poles (see fig. 29), and effectively earthed at arranged points, the danger of flashover of line insulators is reduced, and, in the case of wood poles, the danger from shattering by lightning stroke is also reduced. The best protection is given by using an earth wire of high conductivity, such as cadmium copper wire, steel-cored copper or aluminium wire. The combined use of the neutral conductor and overhead earth wire offers high-conductivity material, greatest safety, and flexibility. This combination on a wood pole line is found to reduce the tendency of pole and crossarm shattering. Also, insulators on wood poles are found to deteriorate much slower than similar insulators on steel poles. The operating value of the overhead earth wire is further increased when it is insulated from the poles as shown in fig. 29.

Although the wood pole has an insulating resistance to lightning voltage equivalent to 100 to 300 kV per foot of height, depending on the wetness or dryness, there is great need of a substitute for wood in pole construction. This need has been steadily increasing, not only because the costs are increasing, but because pole lines in general by force of circumstances require a more permanent type of construction. As cost of materials and of labour increases, there is created the necessity for justifying higher first cost of a more permanent construction by reason of longer life, lower maintenance

cost, greater reliability, and more uniform strength factor in terms of life and hazards.

Whether we use the wood pole construction or any other line construction, the time has arrived when we must think more seriously of obviating as far as possible flashovers and short-circuits due to birds and atmospheric disturbances. With respect to the majority of troubles, disturbances, interruptions and unsatisfactory service as the result of birds, there is very little justification in keeping to the flat crossarm and then providing all sorts of so-called bird-guards to prevent troubles. Prevention is better than cure, and the types of arms shown in figs. 29 and 30 completely mitigate bird troubles and offer a more substantial, safer, and cheaper line construction for wood, steel, or reinforced concrete pole lines.

Wood construction has the advantage of better insulation per pole, but more poles (with insulators) are required than for steel or reinforced concrete construction. For a humid atmosphere like ours, it can be taken for granted that the insulation of a well-constructed and maintained wood pole line is very little (if any) better than that of a reinforced concrete pole line with much longer span, but is decidedly better than in the case of a steel pole line. The relative merits from this viewpoint depend, of course, on whether the insulator pins on the reinforced concrete line are metallically bonded to the reinforcing steel of the pole itself, and whether the steel extends beyond the pole base and is well earthed.

The rust factor for exposed steel is very high, this making a permanent item of maintenance expenditure as well as causing the strength factor to be uncertain and possibly of a dangerous value. Defective maintenance of steel pole construction, coupled with the high first cost as compared with wood, and the depreciated insulation strength, with relatively greater lightning hazard, especially at the pole, have led to a closer study of a more durable and dependable design and construction.

The reinforced concrete pole of the solid type, in particular, is characterised by all the desired fundamentals, some of which are: the imperishableness of solid, hard stone; strength of steel coupled with most perfect protection from atmospheric and climatic influences; and an almost unequalled facility (as compared with wood or steel) for forming and shaping. These inherently excellent properties are likely to be degraded by inferior design and construction, such as, for instance, casting tubes or pipes of thin shell telescoped for a short length into each other for the purpose of obtaining the desired pole-length. Chiefly due to certain types

and designs, discredit may fall on reinforced *concrete pole line* construction. Independent of type and design, perhaps the greatest disadvantage is the heavy weight of the finished cast piece, which, for any type of construction destined for transportation, increases costs, difficulties of transport, and dangers from fracture, etc. Some designs have aimed at casting in the form of a shell, and, to ensure light weight, casting separate sections either to be bolted, clamped or telescoped—all for the express purpose of qualifying a construction destined for dangerous and expensive transportation. In consequence of these attempts the *combined* mass (steel and concrete) is not being worked to best advantages of both materials, but is uncertain and irregular in properties and characteristics, and there is every chance for high maintenance costs in keeping high factors of safety due to early developed faults and to a long series of possible weaknesses due to type, design, casting, transport, hauling, handling, and erecting, all of which can and do influence the factor of safety. The question therefore arises how best to mitigate one or more of these weaknesses and reduce excess costs, etc., and obtain a better and more permanent factor of safety.

Concrete is only about one-tenth as strong towards tension as it is towards compression. Steel, by itself, to resist compression, must be made in forms to give ample lateral rigidity; this favours steel braced with concrete. When the two materials are arranged in one member so that the steel will resist the tension and the concrete the compression, great strength advantage over all-steel or wood construction results. In the reinforced concrete pole, a thorough bonding together of the steel and concrete is most desirable. Bonding resistance is therefore highly important; it is intimately related with the preliminary stretching and the anchoring of the reinforcing steel-rods, as well as with the method of curing and setting the concrete. The bonding is strongest when the steel has received a preliminary expansion, and when the concrete has been stored in water or in the moist wood forms; it is weakest when the concrete has been air-stored and set under external pressure. These are very important factors to observe when casting and curing reinforced concrete poles of the hollow type with moderately thin shell.

A few of the advantages of reinforced concrete over steel or wood are: greater durability, non-rusting, non-decaying, fireproof, almost total absence of maintenance costs, does not require any preservative, is not attacked by thermites, when properly made is not attacked by salt or acid (air or moisture) from the atmosphere,

is readily adaptable to any shape, and is easily dimensioned to any load. However, counteracting these excellent advantages are uncertainty in methods of casting and curing, treatment and grade of steel, thickness of concrete covering the steel, and figures relating to reinforcement of the section, etc. The reinforced concrete pole is jeopardised by present methods of using the steel and proportioning of the concrete and steel. To lessen the heavy weight and cost of transport and handling, makers have sought various processes of casting poles either as hollow shells or/and in separate sections. The former methods endeavour to force up the strength of a given concrete mass-section, with the result that hair-line cracks are far too common, due to the relatively thin shell of concrete and the relatively high expansion-coefficient of the steel, etc., which condition results either in failures or in decreased life and strength; the latter methods endeavour to facilitate transport by casting poles in sections with telescopic or butt jointing, both of which are undesirable, and offer a pole with joints that, for equivalent total unit length and cost, is weaker and becomes still weaker with age, resulting in increase of the maintenance cost, etc.

For any given cross-section, the solid one-piece pole is always the strongest and the most reliable, but by all past methods of making it costs more, due to the higher cost of transport and handling and to the extra concrete. To offset these objectionable and unnecessary costs we must reduce the costs of transport, etc. already mentioned. Then we can not only build a reinforced concrete pole line at a total initial first cost practically equivalent to that of a wood pole line of equal strength, but build a pole line of decidedly superior strength, resulting in an almost immediate decreased (ever on the decrease) annual expenditure, with consequent increase (ever on the increase) in reliability and substantial decrease in the 90 per cent. external troubles already referred to.

When comparing the concrete pole and the wood pole *lines* (not pole only), the merits of the former are soon made evident:

(1) No preservative is required and little or no maintenance cost is involved with the concrete. The concrete pole line becomes stronger with age and it takes care of itself (at least as well as the best wall of any concrete building).

(2) Relative life favours concrete construction, especially the solid concrete pole which is made from rich proportions and is finished off while damp with a rich mixture that interjoins organically with the damp pole and thus seals and tightens all possible slight wounds.

(3) Longer spans can be used with better all-round re-

liability; the first cost is very little higher, and the little extra cost is more than worth the advantages gained, because a concrete pole *line* becomes relatively less and less *expensive with* time, *i.e.* it becomes increasingly *cheaper and much more* dependable with time as compared with the wood pole *line.*

(4) As the great majority of system troubles and interruptions are due to insulators, wires, and birds, with the concrete construction shown in fig. 30 the number of insulators is less per mile of line and troubles from birds are entirely eliminated. The concrete pole is flexible and is more dependable for balancing-up unequal span-stresses. Also, the flexibility and strength of a concrete pole line are very much more constant with age, as compared with a wood or a steel pole line.

The *allowable* pull on reinforced concrete poles is generally based on a working stress which, for steel, is about 17,000 lb./sq. in., and for concrete about 750 lb./sq. in. Such a steel would have an ultimate strength of about 55,000 lb./sq. in., and a yield-point of not less than 34,000 lb./sq. in. For high-grade concrete we may take 850 lb./sq. in. as the highest bending compression. A factor of safety of 3·5 for steel will require more steel or the use of a higher grade steel with a yield-point of not less than 50,000 lb./sq. in. as compared with

$$34{,}000 \times \frac{2 \cdot 5}{3 \cdot 5} = 24{,}300 \text{ lb./sq. in.}$$

One difficulty in using such higher-grade steel is that it must be warmed before bending. Mild steel is bent cold and has the convenience of being able to be stretched or twisted while cold.

The compressive strength of concrete may be taken at 2600 lb./sq. in., based on testing in usual compressive cubes. This gives a factor of safety of $2600/750 = 3 \cdot 5$, but, as reinforced concrete sustained to bending moments will show from 30 to 40 per cent. higher compression strength (especially when the steel is first given a preliminary expansion), in a pole sustained to bending moments the factor of safety for the concrete will be much nearer

$$2600 \times \frac{1 \cdot 3}{750} = 4 \cdot 5.$$

Taking the *allowable* bending compression as 750 lb./sq. in., there is just reason for assuming that the first minute cracks or hair-lines (although not visible to the naked eye) will appear when a pole of the hollow or shell-type and ordinary shell thickness is subjected to a stress no greater than 30 per cent. of the ordinary

working stress, where the reinforcing rods have not previously been given a preliminary stretch; these hair-lines will increase in number and will broaden and lengthen as the working stress is increased up to the full allowable value. Many of the troubles attributed to improper curing or puddling, or high water-content, etc., have simply been the result of insufficient depth of steel covering or thickness of concrete, and using a form of reinforcement of the cross-section of the pole (especially the round or curved figure) where the steel tension on individual rods of the same or different length varies widely due to different respective positions within the figure, or too small a proportion of concrete, or neglect of preliminary expansion of the steel, or because means are not available for making the steel assist the compression of the concrete *after* the latter has hardened. The solid (or the *very thick* shell type) pole has all the advantages, and this is the case especially with the solid type; the steel is well embedded in concrete and, during and after a sufficient hardening period for the concrete, the reinforcing rods endeavour to contract, but, owing to the adhesion of the concrete, this creates a compression of the concrete throughout the whole sectional area of the pole. This compressive condition gives a very high security against cracks as compared with all present-day and past methods of making. The greatest security is obtained when the rods have received a preliminary straining and stretch at the time of casting the pole and are secured and held from possible contraction until the concrete is thoroughly hardened. This condition creates in the concrete a very important additional compression strength, the magnitude of which varies with the chosen figure of reinforcement (the best type is that of solid poles of square or rectangular outline). This practice was adopted by the author when making reinforced concrete poles abroad.

The total drawing capacity acting equally on *all* longitudinal rods should be given by $T = eA_s$. During the time the concrete is thoroughly hardening, the steel rods endeavour to contract to their original length, but the surrounding concrete prevents this and in this way compression in the concrete is caused. This results in a better concrete, also an excellent, desirable state of equilibrium of steel and concrete.

In the practice of casting reinforced concrete poles it should be sought to equate

$$eA_s = e'A_c.$$

This should result in an axial compression over the whole cross-section, making

$$e' = e(A_s/A_c) = Be,$$

where

e = preliminary expansion of the steel (very rarely practised).

B = figure of reinforcement of the cross-section of pole.

A_s = area of the steel.

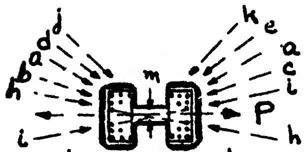
A_c = area of the concrete.

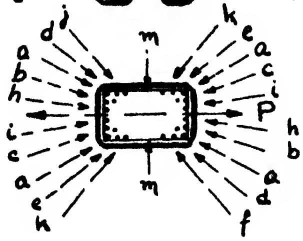
About 440 lb./sq. in. can be reckoned as a *preliminary expansion force* for the steel. Below 440 lb./sq. *in. concrete bending* tension the first minute cracks may appear but are not visible to the naked eye. If a preliminary expansion is first given to the steel, almost double the security can be secured against cracks (similar results can, of course, be achieved either by increasing the mass of concrete or by decreasing the expansion given to the steel, or *vice versa*). Thus, in actual practice, it is the high proportion of concrete to steel that matter and is most relied upon; with a very small proportion of concrete however, as in hollow types of poles, preliminary expansion of the steel is the best possible procedure.

A total preliminary steel expansion force of 8800 lb./sq. in. is approximately equal to 5 per cent. steel reinforcement, that is, 440/8800 = 0·05, and a 5700 lb./sq. in. preliminary steel expansion force is approximately equal to 7·5 per cent. steel reinforcement, or 440/5700 = 0·075. The lowest value of reinforcement, resulting from the elastic limit of the steel, is not less than 1·6 per cent., which value is theoretical. As hair-line cracks form the real beginning of most weakening troubles and failures, by exposure of the steel to acids, salt, air and moisture, this steel expansion process is certainly most important and necessary in the casting and making of poles of the hollow or shell types, with or without curved outlines. When using unstretched steel in the *hollow* type of pole, excess concrete pressure can much more easily be borne by the reinforced concrete than the very smallest excess lateral pull (or draw) which, through the minute loosening of the concrete texture, exposes the steel, causing its rapid weakening or failure. With the *solid* type of pole, preliminary expansion of the steel is not so necessary; the solid rectangular type of pole is the strongest and most reliable, being followed by the solid square type.

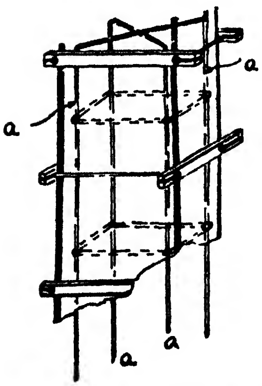
Independent of the concrete mixture and many other factors, the factor of safety of a reinforced concrete pole is intimately interrelated with the preliminary expansion of the steel and the figure of reinforcement of the cross-section of the pole. These are two vital factors and require that a shell or hollow type of pole shall be designed to a higher *steel* factor of safety than a solid pole of equal diameter. They show most clearly that a solid construction is

"H" Type.





Rectangular Type.



Wooden form, panels and braces with the four (corner) longitudinal rods.

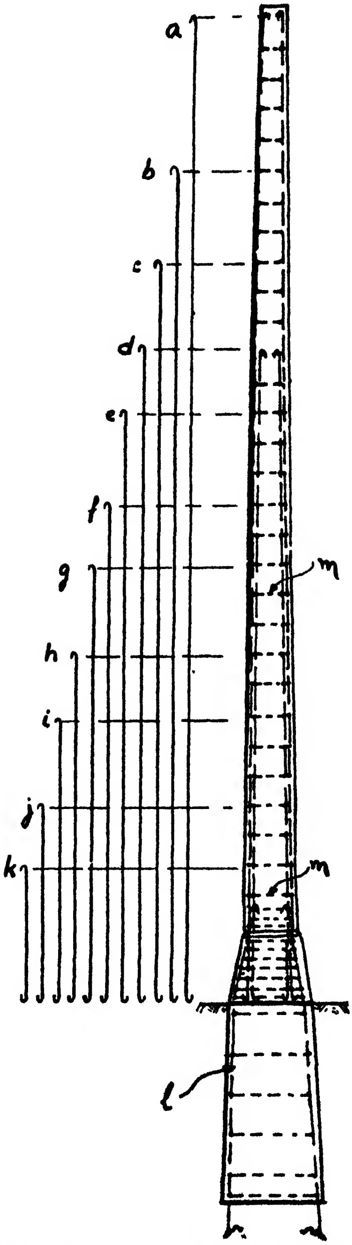


FIG. 52.—Showing Super-strength Type of Reinforced Concrete Pole and one method of Arranging the Reinforcing Steel. This pole is both *formed* and *cast* in its final position, or may be formed at any angle but always cast in its final position. (See fig. 54.)

safer and more durable than a hollow construction designed to the same factor of safety. Also, apart from these and other advantages of the solid construction, most shell or hollow type constructions are subjected to uncertainties of strength, to very narrow limits of depth of steel, to greater facility for developing hair-line cracks with relatively less loading, to irregularity and unevenness of strength and of keying and bonding of the steel, to weaknesses caused during mixing, casting, curing or handling at the works, to excess of material and/or weakening from thickening, tapering or jointing, etc. Also, compared with the strength of a wood pole, which is by no means uniform for a given timber (fir or any other), the reinforced concrete pole of the hollow type is little better in respect of this variation, due to one or another of the many already-mentioned causes and hazards, commencing from the casting at the works, and continuing all the way through the series of operations, transit and handling, to the completed erection in the line.

Of the two materials used, concrete is the most inconsistent and may be of relatively little strength value for certain shell types of poles, yet be of very great strength value and offer very substantial lateral rigidity to *all* the steel rods in solid poles of almost any figure, more especially of the rectangular and similar shapes, which offer low resistance to lateral winds (for which every pole is designed). Concrete of sufficient thickness gives the greatest and most uniform steel strength, and in the solid type is offered the best figure of reinforcement with the most effective cross-section for equal or less lateral diameter. The only disadvantages of the solid pole have been the difficulties and high costs associated with transport, haulage, handling and erection. However, the whole of these (without a single exception) have been now entirely overcome by a new method of forming and casting the poles, *i.e. they are formed and cast in their final position in the line.*

Before explaining the merits of this new type of construction and its influence in effecting a large reduction in total costs and in obviating the 90 per cent. of troubles already referred to, we may first outline the factors of safety for *steel* at present imposed by law; these are:

(1) For steel conductors, with or without a thin film of galvanising	2·0
(2) For steel (exposed) for poles and structures, with or without a thin film of paint or galvanising .	2·5
(3) For steel (for reinforced concrete) *always sustained and completely embedded in concrete* . .	3·5

The idea in (3) is akin to specifying a weak pole (using too *low* a factor of 3·5 for concrete), then deliberately wasting expensive material (requiring a most unjustly *excessive* factor of 3·5 for steel) in the unsound endeavour to make the whole strong.

The factor of safety of 3·5 may be no more correct for steel than for concrete; it may be unsound for both materials, being much too low for one and much too high for the other, but it may not be unsound to expect the inherent distinct properties and characteristics of the materials to even-up or most economically assist each other. Due to this manner of specifying an even factor of safety for radically different materials, the hair-line crack dangers and problems are much intensified for the hollow type of poles; owing to the vastly different characteristics of the two materials, the two factors should be separated, and it is suggested that they should be:

Factor of safety for steel . . .	2·0 to 2·5,
Factor of safety for concrete . .	4·0 to 4·5,

calculated on the elastic limit (yield-point) or crippling load of the materials.

It should never be overlooked that the strength and real factor of safety of reinforced concrete poles vary with the types and methods of casting, whether the poles are formed and cast *in the actual final positions in the line*, or formed and cast far remote from the sites in which they are to be used, and are influenced by the methods and means of handling, of transport by rail, of road haulage by vehicle, and the handling and erection after haulage operations. The shell type of pole is the most susceptible to damage by any one of these operations, and the damage may not show up until after erection and the pole is loaded. The hollow telescopic type of pole is still weaker, due to the joint, form, etc. The factor of safety of a pole may sometimes be increased by an additional 2·0 to allow for weaknesses arising out of the ill-effects of transit by rail, haulage by road, handling to site, and erection. What is desired is the stronger solid pole, a pole sound from the core to the surface, one offering the most effective strength of all the steel in the pole and the whole used for the *truly* lateral calculated strength due to the steel, having the best figure of reinforcement of cross-section and the best mass of concrete to produce and give the desired state of concrete and steel equilibrium, and offering the highest security against cracks or hair-lines for all loads, especially the actual maximum working loads.

When cast in its vertical position the plastic vertical mass is

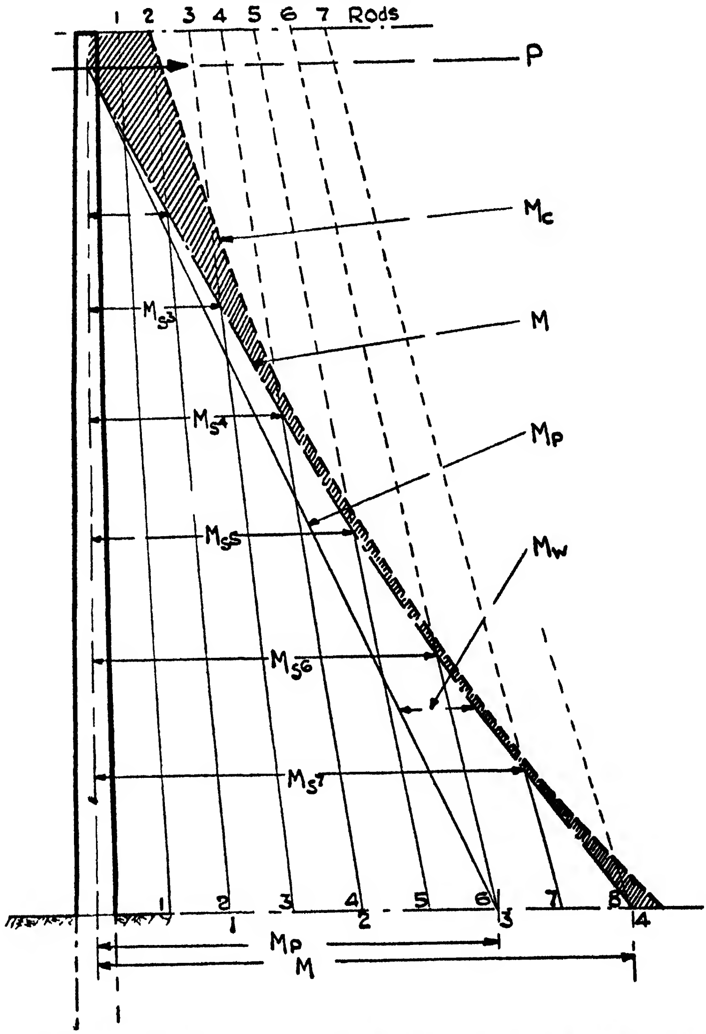
weighted down and settles to the greatest density and strength just where these are most required; the *moist* mass in the wet wooden forms allows of the best manner of curing for hardness and strength; the best possible compression of the concrete can (as desired) be obtained by first giving a preliminary expansion to the steel longitudinal rods and by using ample concrete mass, such as a rectangular or square of *solid* section, this procedure offering the greatest security against hair cracks during ordinary or any loading, this not obtaining with the shell type of pole, which readily permits a loosening of the texture at 50 per cent. or very much less than full load and sufficient ultimately to cause weakness and failure. The higher proportion of concrete in the solid type of pole, as also the figure of reinforcement, give a greater concrete bending compression and in consequence a greater security against cracks—in other words, a more reliable and durable pole. With a preliminary expansion of the steel, the solid pole of rectangular shape (the narrow sides in the direction of the calculated loads), formed and cast in its final position in the line, offers not only the cheapest, best and safest construction (both mechanically and electrically), but the most dependable, both mechanically and electrically (see figs. 30, 52 and 54).

Figs. 52 and 53 refer to a type of reinforced concrete pole construction that incorporates the following advantages over wood, steel, and reinforced concrete poles of other designs: greater mechanical strength for smaller overall diameter; flexibility, with highest degree of safety and usefulness; total freedom from bird troubles; high inherent protection from induced potentials and best facilities for earthing line equipment without the use of any exposed metal; lowest cost of *any type* of reinforced concrete pole of equal strength, etc., etc. In other words:

(1) A steel reinforcement and disposition for pole, fixtures and foundation is afforded, to balance or level-up most economically the pole strength on parallel faces, independent of the pole shape, and always with much greater strength in the direction of the greatest stress whether for transverse or longitudinal directional forces. This provides not only the most economical amount of steel exactly where it should go for greatest strength requirements, but it also provides a levelling-up of the steel to afford maximum economy with maximum strength (see fig. 52).

(2) The erection of the *form* (complete or in part) and the casting of the *pole*, frame or structure, or/and fixtures (arms and so forth) or/and foundation, are carried out *all* in the

FIG. 53.—Method of Calculating Bending Moments for Pole shown in fig. 52.



M_c = Moments curve for concrete. The value must be kept at or below the allowable working stress of the concrete.

$M_s^1, M_s^2, M_s^3, M_s^4$, etc. = Respective cross-sections reinforced with s per cent. of steel and sustained to a bending moment equal to the respective values of M.

M_p = Bending moments due to horizontal pull (P).

M_w = Bending moments due to wind on pole.

M = Resultant bending moment due to horizontal pull and wind load on pole ($= M_p + M_w$).

(The number of longitudinal rods will depend on the section tensile strength within the allowable working stress for steel. For the example shown here: To take the pull P, the pole may be reinforced with eight steel rods of the respective lengths shown, or, four or six steel rods may be alternately disposed as shown in fig. 52.)

actual final positions on the line, and so that no scaffolding or superstructure is required for any of the operations. The ever-present danger of fracture or weakness, as well as the excessive costs of transport, haulage, handling, and erection, all cancel out. Such dangers and high costs cripple the more extensive use of reinforced concrete poles from a competitive standpoint, and the cancelling out of the ever-present danger of fracture or damage ensures a more favourable factor of safety. Apart from this, a solid, much stronger and more reliable pole is possible at less cost, and the concrete attains a greater density and strength (particularly at those points where greatest strength is most required) than in the case of the same pole cast horizontally. The pole is puddled or/and tamped in the process of erection, and the concrete pressed tight and weighted downward so that it hardens and possesses less moisture content. The pole is further strengthened by casting its foundation directly against undisturbed natural ground without any filling-in or falling-in of earth, since the foundation forms the first operation, and not the last as with all other methods (see also fig. 30).

(3) The arms for insulators are metallically bonded internally to the steel of the pole and the foundation. They are of a form permitting of the three chief requirements, namely: *total* freedom from bird troubles; *lowest* possible reduction in calculated height of load application (which allows of a relatively slight reduction in the factor of safety); *highest* possible elevation of the insulator-base above ground-level; use of single or double insulators in parallel (required for main roads and crossings) or in series, or both (see fig. 30). The entire steel reinforcement (fixtures, pole and its foundation) is bonded, well earthed, and sealed outlets are provided (as desired for plugging in) for earthing any line equipment (such as transformers) without the necessity of exposed or encased wires running over any part of the pole surface.

Fig. 53 shows a typical method of calculating the bending moments for this design of reinforced concrete pole. It shows that, in a cross-section reinforced with s per cent. of steel and sustained to a bending moment M^1, the stresses in the steel and concrete are S_s and S_c, respectively. If we assume that these stresses are lower than the allowable working stresses S_s' and S_c', then, should the bending moment be increased, the stresses in the steel and concrete will also increase. When the moment has reached the value M_s,

the stress in the steel is S_s, also, at the equivalent value M_c the stress in the concrete is S_c. By plotting the moment values M_s^1, M_s^2, etc., according to the number of reinforcing rods required for the load, we arrive at the allowable transverse pull and derive the number and respective lengths of the steel rods required. When the pole is sustained to a horizontal pull of P (say 2 ft. from the top of the pole), the moment will be represented by a straight inclined line, as shown in fig. 53 for M_p, extending to the ground line; the value at the latter is equal to bending moment M_p. The wind load on the pole gives a bending moment M_w, and when this moment is added to M_p we obtain the resultant total bending moment M. The value of the latter must (for the whole pole length above ground line) be kept within the moment value M_c, to keep the respective compression stresses in the concrete below or no greater than the allowable working stress value. The weakest point of the pole can always be found, and is seen at a glance by plotting a bending moments diagram for the respective stresses in the manner laid down here; its position on the diagram will be where the resulting moment M is nearest to the moment M_s. For a given diameter and the same percentage of steel, a solid pole will resist much greater bending moments than a hollow type of pole; a square section pole will take greater bending moments than a hexagonal pole, and a rectangular pole more than a square pole.

A set of calculations and costs are given below for a range of standard sizes of copper conductors, based on ample minimum overhead clearance of the conductors, and present Regulation loading conditions. It has already been noted but may be repeated, that this particular reinforced concrete construction is the safest, best, and most reliable type of line design and construction due to the fact that it is totally free from *bird* troubles (see type of arms, fig. 30); it is the most reliable from the protective standpoint for both line and terminal apparatus, because it is the most flexible and durable with stability of the initial factor of safety; it is the most lasting of any type of construction, more durable than wood, steel and all other types of concrete poles; and it is cheaper and better than wood or steel construction in terms of initial cost plus gross annual expenses.

As regards the initial first costs, which form the starting-point for consideration and comparison, these can best be understood from the following examples of practice. A method of calculation for the reinforced concrete pole has been simplified and brought down to a basis repeatedly recommended by the author for this and the compound wood pole construction, *i.e.* to terms of stresses

or moments for plotting to a stress or a moments diagram, respectively, such as that shown in fig. 53.

Calculations for Reinforced Concrete Pole Lines.

(Based on the present factor of safety of 3·5, which combined factor is more costly than 2·5 for steel and 4·5 for concrete.)

Design Factors.	Sizes of Copper Line-conductors (sq. inch).				
	0·05	0·075	0·10	0·15	0·20
(Physical Data):					
Line voltage	3300 to 15,000	3300 to 15,000	3300 to 15,000	15,000 to 33,000	15,000 to 33,000
Number of conductors	3	3	3	3	3
Weight, lb. per ft. of length	0·200	0·300	0·398	0·594	0·802
Radial ice-coating, inch	$\frac{3}{8}$	$\frac{3}{8}$	$\frac{3}{8}$	$\frac{3}{8}$	$\frac{3}{8}$
Type of insulators used	pin	pin	pin	suspension	suspension
Height of pole above ground, ft	33	33	33	42	42
Horizontal conductor separation, inches	48	48	48	60	60
Vertical conductor separation, inches	36	36	36	60	60
Distance from pole top to top conductor, inches	6	6	6	21	21
Distance from pole top to lowest conductor, inches	36	36	36	84	84
Minimum clearance of conductors above ground, ft	20	20	20	22	22
Relative number of poles per 10 miles of line	114	106	91	85	81
Number of anchor poles per 10 miles of line	10	10	10	10	10
Number of straight line poles per 10 miles of line	104	96	81	75	71
(Straight-line Construction):					
Horizontal wind load per conductor, lb. per ft. of length for 8 lb. per sq. ft. wind	0·71	0·758	0·77	0·83	1·018
Allowable tension of conductor, lb.	1536	2240	3032	3202	5829
Total horizontal wind, lb. per ft. of length	2·13	2·27	2·31	2·49	3·054
Span length, ft.	467	500	583	624	655
Total horizontal load for span, lb. (x)	994·5	1140	1347	1557	2000
Mean height of load application above ground, ft. (y)	21	21	21	40	40
Calculated load which, when applied at pole top, gives the same bending moment at ground line as x applied at distance y below top of pole, lb.	940	1078	1274	1433	1840
Regulation wind load on pole, lb. per sq. ft.	13	13	13	13	13
Calculated pole top dimensions, inches	9×6	10×6	10×6·5	11×6·5	11×7
Calculated allowable lateral pull, lb.	948	1120	1320	1530	1842

[Continued over.

Calculations for Reinforced Concrete Pole Lines.—*Continued.*

Design Factors.	Sizes of Copper Line-conductors (sq. inch).				
	0·05	0·075	0·10	0·15	0·20
(*Anchor Construction*):					
Ultimate strength of copper conductors, lb.	3073	4481	6065	8805	11,638
Assuming two broken conductors and tension of 40 per cent., lb. pull	2200	3565	4400	7050	9290
Calculated actual load, lb.	2080	3370	4160	7050	9290
Calculated top dimensions, inches	12×8	14×10	15×10	2–14×10	2–15×10
Calculated allowable lateral pull for anchor poles, lb.	2580	4020	4890	8050	9780

Cost of Construction.

(*Reduced to cost per mile of length.*)

	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)	Unit Price.
Cement: Delivered nearest railway station; based on 750 lb./sq. in. concrete stress	32·7	360	36·4	400	34·8	383	50·6	557	55·8	614	11s. per barrel.
Sand and Gravel: Delivered at pole site	490	638	547	712	528	688	760	990	840	1093	1s. 4d. per sack.
Rubble Stone: For the foundations; delivered at pole site	9	27	11	33	10	30	15	45	18	54	3s. per cub. yd.
Steel Reinforcement: Yield-point of 50,000 lb./sq. in.; delivered at nearest railway station	7·5	450	7·97	478	7·85	471	11·4	684	11·9	715	60s. per 1000 lb.
Wood Forms: Based on forms being used 10 times only, then scrapped	212	124	212	124	200	113	252	147	264	149	7d. per sq. yd.
Labour: Including cost of labour for transporting wood forms and equipment from pole to pole and other materials from nearest railway station to respective sites	710	852	745	906	695	835	920	1105	1000	1200	1s. 2d. per hour.

[*Continued over.*

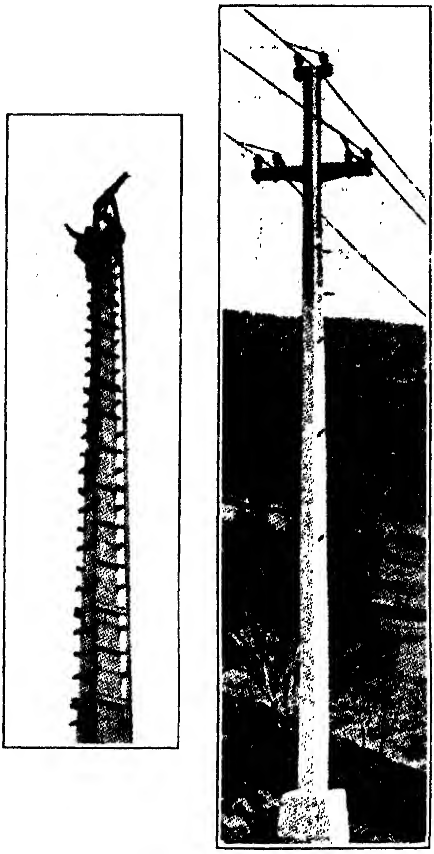


FIG. 54.—Showing method of *casting* solid reinforced concrete poles *vertically in their final positions in the line.* The centre illustration shows a pole installed and working; the universal crossarm and double-insulator construction is used in this installation. The illustrations on the right and left show a condition where the casting (raising and filling with concrete) has just been completed. The workmen move up and/or down the pole-frame as desired without the aid of climbers or implements of any kind. The concrete is poured in at the top or through open panels of the wooden forms as desired or found most convenient. The wooden forms are kept in place until the concrete has set sufficiently hard. The stripping of the forms is then carried out from the top downwards.

Cost of Construction.—*Continued.*

	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)	Unit Price.
Transport of materials from railway station to pole site . .	10·9	273	11·8	295	11·3	283	162	405	17·4	435	25s. per ton.
Overhead Expenses .	15·3	295	16·3	315	16·0	308	23	443	24·4	470	19s. per cub. yd. of concrete.

Cost per Mile of Line, excluding conductor and insulators . .	3023s.	3363s.	3111s.[1]	4386s.	4730s.
	£151 3 0	£168 3 0	£155 11 0	£219 6 0	£236 10 0

(a) *Item for quantity of materials.*
(b) *Item for cost of materials in shillings.*

Reinforced concrete construction is the truly modern and ultimate type of construction for overhead power lines whether they are for 230 volts or for the highest voltages for which power transformers can be built. It is not difficult to see that the reinforced concrete pole line construction is the one giving all the most desirable operating and maintenance requirements. By a careful comparison it is also seen that the first cost of a reinforced concrete pole line compares well with the wood pole line for equal (new) strength of the latter. However, such a cost basis is inaccurate and unsound, since a reinforced concrete pole line with a first cost much higher than a wood pole line, for the type of construction given here, can actually be cheaper in the long run than the wood pole line, because the latter is burdened with a high *permanent* maintenance cost. In order to make this clear, the following is given as an example of practice that best favours the wood pole line, that is to say, with the smallest size of conductor for rural lines (obviously, the heavier power transmission line favours reinforced concrete). Hence, specially to favour the wood pole line, the following smallest conductor line is given for wood, steel, and

[1] This price is slightly less than that for the next smaller size of copper conductor line, due to the fact that the spans are longer, thus resulting in a lower figure for number of poles per mile of line. The overhead expenses are reduced to cost per cubic yard of concrete in place, and include insurance, depreciation on equipment, supervising, miscellaneous supplies, travelling expenses and other contingencies. These expenses, as also the unit prices given, are considered quite reasonable. The quantities are accurate for the calculated loadings and designs proposed by the writer. Therefore, the above figures of costs are reliable and are sufficiently detailed for engineers to check and compare with their wood and steel pole lines.

reinforced concrete, with operation and maintenance carried over a period of twenty years.

Costs per Mile of One Three-Phase, 0·025 sq. in. Copper Cable, 11,000-volt. Primary Distribution Line.

	£	s.	d.
Wood Pole Line.			
23 poles, including haulage and erection	£46	5	0
23 crossarms, in place	18	2	0
12 foundation wooden baulks	9	3	0
1 strut for anchor or angle pole	2	0	0
90 insulators, which include a minimum number of double insulators along public roads and at crossings	17	10	0
90 galvanised insulator pins	7	2	0
440 lbs. of earth wire with connections to plates	3	3	0
1000 lbs. of 0·025 sq. in. copper conductor	48	10	0
Necessary earth plates	3	3	0
Haulage of materials (not poles)	8	0	0
Stringing, etc.	14	2	0
	£177	0	0
Insurance, depreciation on equipment, supervision, miscellaneous supplies, danger signs, superintendence, and unforeseen expenses (15 per cent.)	26	5	0
Total First Cost per Mile of Line	£203	5	0
Steel Pole Line.			
8 poles and arms, including haulage and freight	£80	0	0
Complete pole erection	32	0	0
33 cub. yds. of concrete for foundations	48	0	0
32 insulators, including double insulators along public roads and at crossings (as for wood poles)	6	3	0
32 galvanised insulator pins	3	4	0
440 lbs. of earth wire with connections to plates	2	10	0
1000 lbs. of 0·025 sq. in. copper conductor	48	10	0
Necessary earth plates	2	16	0
Haulage of materials, etc.	4	10	0
Stringing, etc.	10	17	0
	£238	10	0
Insurance, depreciation on equipment, supervision, miscellaneous supplies, danger signs, superintendence, and unforeseen expenses (15 per cent.)	35	16	0
Total First Cost per Mile of Line	£274	6	0
Concrete Pole Line.			
Poles and crossarms complete in place	£128	0	0
36 insulators, including double insulators along roads and at crossings (as for the wood pole line)	7	1	0
36 galvanised insulator pins	2	17	0
440 lbs. of earth wire with connections to plates	3	3	0
1000 lbs. of 0·025 sq. in. copper conductor	48	10	0
Necessary earth plates	3	1	0
Haulage of materials (not poles)	4	4	0
Stringing, etc.	9	14	0
	£206	10	0
Insurance, depreciation on equipment, supervision, miscellaneous supplies, danger signs, superintendence, and unforeseen expenses (15 per cent.)	12	10	0
Total First Cost per Mile of Line	£219	0	0

Annual Expenses.[1]

Wood Pole Line.

Annual capital interest at 5 per cent.	£10 0 0
Depreciation annuities for poles	6 15 0
Depreciation annuities for the remainder of line	5 10 0
(allowance for painting, etc.)	4 10 0
Total Annual Expenses per Mile of Line .	£26 15 0

Steel Pole Line.

Annual capital interest at 5 per cent.	£13 14 0
Depreciation annuities for poles	2 10 0
Depreciation annuities for remainder of line	3 4 0
(allowance for painting, etc.)	2 16 0
Total Annual Expenses per Mile of Line .	£22 4 0

Reinforced Concrete Pole Line.

Annual capital interest at 5 per cent.	£11 0 0
Depreciation annuities for poles	1 2 0
Depreciation annuities for remainder of line	3 4 0
Total Annual Expenses per Mile of Line .	£15 6 0

Summary.

	Wood Pole Line.	Steel Pole Line.	Concrete Pole Line.
Initial cost of construction . .	£203 5 0	£274 6 0	£219 0 0
Upkeep expenses for 10 years .	470 15 0	498 0 0	375 0 0
Upkeep expenses for 20 years .	738 5 0	722 0 0	530 0 0

Thus, in twenty years, the wood pole line will have cost £207, 15s. 0d. per mile *more* than the reinforced concrete pole line, *i.e.* the excess cost alone would have practically paid for the concrete pole line. By using wood poles instead of concrete poles £15, 15s. 0d. per mile in first cost may be saved, but at the same time £10, 9s. 0d. more will be spent per mile each year for maintaining a line of less reliability. In other words, by building a wood pole line in order to save a little in first cost, money is borrowed at nearly 80 per cent. interest per annum for a less reliable line.

Assuming four 11,000-volt circuits aggregating 120 miles in length, and each circuit of 200 kW capacity, or a total of 800 kW, the annual saving with the concrete pole line would mean that the power undertaking could deliver its power at £1, 1s. 0d. per kW cheaper as compared with the wood pole line, the price for transmitting power being that due to total annual expenses. The best

[1] Annual cost items are purposely kept low for the steel pole line and kept high for the reinforced concrete pole line; the wood poles are *butt*-treated only.

power line is that one transmitting power at the cheapest rate (including the relative reliability cost item which favours the concrete pole line). The total annual upkeep costs for the wood pole line are more than *three times* the annual costs usually charged against the capital interest, or upwards of 15 per cent. In view of this, it is very evident that the annual upkeep cost is where the greatest economy should be made, and the higher first cost (if any) disregarded. The concrete pole line is the stronger and more reliable line, and a better line from the transformer system and all other viewpoints. Moreover, it is the type of construction that represents the most modern and the ultimate requirements of electrical engineering practice where overhead lines are used.

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